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An assessment of the CF submarine watch schedule variants for impact on modeled crew performance

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Abstract

Background. In support of the Board of Inquiry (BOI) investigating the October 2005 fire on board HMCS Chicoutimi, DRDC Toronto was asked to model crew cognitive effectiveness at the time of the fire and at the time of casualty evacuation approximately 28 hrs after the fire. The results of this modeling effort (based on sleep behaviour estimates) suggested that our submariners were operating at significantly reduced levels of cognitive effectiveness. Therefore DRDC Toronto was tasked to conduct an at-sea trial, this time using real actigraphically-derived sleep data in order to more accurately model the impact of the watch schedule on crew cognitive effectiveness. **Methods.** Twenty-one submariners participated as subjects in this at-sea trial. Three of these subjects were non-watch-standers: Commanding Officer (CO), Coxswain (COXSN) and Chief Engine Room Artificer (CERA), 6 subjects were from the 1-in-2 back-watch, 6 subjects were from the 1-in-2 front-watch, and 6 subjects were from the 1-in-3 engineers' watch. The trial took place on a Canadian submarine during a 13-day transatlantic return to Halifax. All subjects wore wrist activity monitors (actigraphs) in order to measure their daily sleep patterns quantitatively. The subjects also maintained a daily activity and sleep log, and performed daily iterations of the psychomotor vigilance task (PVT). **Results.** The modeled cognitive effectiveness was worse than the previous modeling efforts for Chicoutimi which used sleep behaviour estimates. The activity and sleep log data indicated increasing difficulty arising from sleep and a decrease in subjective levels of 'restedness' over days at sea. Alertness also decreased over days at sea. Each of the 1-in-2 front and back-watches were less 'happy' than their 1-in-3 engineering watch counterparts. While there was no difference in sleepiness between watch system variants or over days at sea, sleepiness levels were consistently elevated to mid-scale levels. Difficulty concentrating, slowed reactions, level of fatigue, work frustration and physical discomfort increased during the trial relative to the pre-trial baseline. **Conclusion.** The current submarine watch schedule is sub-optimal in that it results in worrisome levels of cognitive effectiveness in our submariners. **Recommendation.** An alternative watch schedule which is more sparing of submariner cognitive effectiveness should be developed and implemented, if possible.

Résumé

Contexte : À la demande de la Commission d'enquête sur l'incendie survenu à bord du NCSM Chicoutimi en octobre 2005, RDDC Toronto a créé un modèle informatisé de l'efficacité cognitive de l'équipage au moment de l'incendie et au moment de l'évacuation des victimes environ 28 heures après l'incendie. Cette modélisation (fondée sur les estimations de conduite du sommeil de l'équipage) a permis de conclure que le niveau d'efficacité cognitive opérationnelle de nos sous-mariniers était considérablement réduit. Par conséquent, RDDC Toronto a été invité à effectuer un essai en mer, en utilisant cette fois des données de sommeil réelles colligées par actigraphie, afin de modéliser plus précisément l'impact des horaires de garde sur l'efficacité cognitive de l'équipage. **Méthodologie :** Vingt et un sous-mariniers ont participé à cet essai en mer. Trois d'entre eux ont été affectés à des postes autres que de garde (Commandant, Capitaine d'armes, et Chef des machines -- CERA); six ont été affectés comme vigies de quart arrière, à raison de un tour de garde sur deux; six ont été affectés comme vigies de quart avant, à raison de un tour de garde sur deux; et six ont été affectés comme mécaniciens chefs de quart, à raison de un tour de service sur trois. L'essai a été réalisé à bord d'un sous-marin canadien, au cours d'un voyage transatlantique de 13 jours, à destination de Halifax. Chacun des participants portait un bracelet moniteur (actigraphe) de ses activités, pour permettre de mesurer quantitativement sa structure de sommeil. Les participants ont aussi consigné quotidiennement dans un journal leurs heures d'activités et leurs heures de sommeil, et ils ont effectué des itérations quotidiennes de leurs tâches d'attention soutenue (*Psychomotor Vigilance Task --* PVT). **Résultats :** L'efficacité cognitive de l'équipage, mesurée lors de cet essai en mer, s'est avérée moindre que celle obtenue par modélisation comportementale fondée sur les estimations de conduite du sommeil de l'équipage du Chicoutimi. Les données consignées dans le journal d'activités et de sommeil ont démontré une difficulté croissante des participants à se tirer du sommeil, et une décroissance des niveaux subjectifs de « sensation de repos » à mesure que le nombre de jour en mer augmentait. Le niveau d'acuité intellectuelle des participants est aussi allé en décroissant au fil des jours durant cet essai en mer. Chacune des vigies de quart avant et arrière affectée à un tour de garde sur deux a fait montre d'une attitude moins joyeuse que ses vis-à-vis mécaniciens chefs de quart affectés à un tour de service sur trois. Bien qu'on n'ait constaté aucune différence du niveau de somnolence entre les vigies, ou après un même nombre de jours en mer, les niveaux de somnolence observés se sont tous avérés moyennement élevés. On a aussi constaté chez les participants une difficulté plus grande à se concentrer, des réactions plus lentes, un niveau de fatigue plus élevé, de la frustration au travail, et un inconfort physique accru. **Conclusion :** L'horaire de garde actuel à bord de nos sous-marins est sous-optimal, du fait qu'il entraîne une réduction inquiétante du niveau d'efficacité cognitive de nos sous-mariniers. **Recommandation :** Un nouvel horaire de garde – moins éprouvant pour l'efficacité cognitive du sous-marinier – devrait être élaboré et mis en œuvre, si possible.

Executive summary

An assessment of the CF submarine watch schedule variants for impact on modeled crew performance

M. A. Paul; G.W. Gray; T.E. Nesthus; J.C. Miller; DRDC Toronto TR 2008-007; Defence R&D Canada – Toronto; March 2008.

Background: In support of the Board of Inquiry (BOI) investigating the October 2005 fire on board HMCS Chicoutimi, DRDC Toronto was asked to model crew cognitive effectiveness at the time of the fire and at the time of casualty evacuation approximately 28 hours after the fire. The results of this modeling effort (based on sleep behaviour estimates) suggested that the submariners were operating at significantly reduced levels of cognitive effectiveness. Therefore, DRDC Toronto was tasked to conduct an at-sea trial, this time using real actigraphically-derived sleep data in order to more accurately model the impact of the watch schedule on crew cognitive effectiveness.

Methods: Twenty-one submariners participated as subjects in this at-sea trial. Three of these subjects were non-watch standers: Commanding Officer (CO), Coxswain (COXSN) and Chief Engine Room Artificer (CERA), 6 subjects were from the 1-in-2 back-watch, 6 subjects were from the 1-in-2 front watch, and 6 subjects were from the 1-in-3 engineers' watch. The trial took place on a Canadian submarine during a 13-day transatlantic return to Halifax. All subjects wore wrist activity monitors (actigraphs) to measure their daily sleep patterns quantitatively. The subjects also maintained a daily activity and sleep log, and performed daily iterations of the psychomotor vigilance task (PVT).

Results: The modeled cognitive effectiveness was worse than the previous modeling efforts for Chicoutimi which used sleep behaviour estimates. The activity and sleep log data indicated increasing difficulty arising from sleep and a decrease in subjective levels of 'restedness' over days at sea. Alertness fell over days at sea. Each of the 1-in-2 front and back watches were less happy than their 1-in-3 engineering watch counterparts. While there was no difference in sleepiness between watch system variants or over days at sea, sleepiness levels were consistently elevated to mid-scale levels. Difficulty concentrating, slowed reactions, level of fatigue, work frustration and physical discomfort increased during the trial relative to the pre-trial baseline.

Significance: The current submarine watch schedule is sub-optimal in that it results in worrisome levels of cognitive effectiveness in our submariners.

Future plans: An alternative watch schedule which is more sparing of submariner cognitive effectiveness should be developed and implemented, if possible.

Sommaire

An assessment of the CF submarine watch schedule variants for impact on modeled crew performance

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Méthodologie : Vingt et un sous-mariniers ont participé à cet essai en mer. Trois d'entre eux ont été affectés à des postes autres que de garde (Commandant, Capitaine d'armes, et Chef des machines -- CERA); six ont été affectés comme vigies de quart arrière, à raison de un tour de garde sur deux; six ont été affectés comme vigies de quart avant, à raison de un tour de garde sur deux; et six ont été affectés comme mécaniciens chefs de quart, à raison de un tour de service sur trois. L'essai a été réalisé à bord d'un sous-marin canadien, au cours d'un voyage transatlantique de 13 jours, à destination de Halifax. Chacun des participants portait un bracelet moniteur (actigraphe) de ses activités, pour permettre de mesurer quantitativement sa structure de sommeil. Les participants ont aussi consigné quotidiennement dans un journal leurs heures d'activités et leurs heures de sommeil, et ils ont effectué des itérations quotidiennes de leurs tâches d'attention soutenue (*Psychomotor Vigilance Task* -- PVT).

Résultats : L'efficacité cognitive de l'équipage, mesurée lors de cet essai en mer, s'est avérée moindre que celle obtenue par modélisation comportementale fondée sur les estimations de conduite du sommeil de l'équipage du Chicoutimi. Les données consignées dans le journal d'activités et de sommeil ont démontré une difficulté croissante des participants à se tirer du sommeil, et une décroissance des niveaux subjectifs de « sensation de repos » à mesure que le nombre de jour en mer augmentait. Le niveau d'acuité intellectuelle des participants est aussi allé en décroissant au fil des jours durant cet essai en mer. Chacune des vigies de quart avant et arrière affectée à un tour de garde sur deux a fait montre d'une attitude moins joyeuse que ses vis-à-vis mécaniciens chefs de quart affectés à un tour de service sur trois. Bien qu'on n'ait constaté aucune différence du niveau de somnolence entre les vigies, ou après un même nombre de jours en mer, les niveaux de somnolence observés se sont tous avérés moyennement élevés. On a aussi constaté chez les participants une difficulté plus grande à se concentrer, des réactions plus lentes, un niveau de fatigue plus élevé, de la frustration au travail, et un inconfort physique accru.

Interprétation : L'horaire de garde actuel à bord de nos sous-marins est sous-optimal, du fait qu'il entraîne une réduction inquiétante du niveau d'efficacité cognitive de nos sous-mariniers.

Recommandation : Un nouvel horaire de garde – moins éprouvant pour l'efficacité cognitive du sous-marinier – devrait être élaboré et mis en œuvre, si possible.

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1   Background

In support of the Board of Inquiry (BOI) investigating the October 2005 fire on HMCS Chicoutimi, the submarine surgeon asked us (DRDC Toronto) to generate a FAST^{TM} (Fatigue Avoidance Scheduling Tool) model to demonstrate the cognitive effectiveness of the submarine crew during the fire and at the time of casualty evacuation approximately 28 hours afterwards. FAST^{TM} is a software program which predicts performance. The inputs to FAST^{TM} are two streams of data; actigraphically-measured daily sleep and daily duty hours. The output of FAST^{TM} is cognitive effectiveness. An actigraph is a small accelerometer about the size of a wrist watch and is worn on the wrist. Based on a reduction algorithm, an actigraph provides a motion-based estimate of daily sleep quantitatively to the nearest minute for weeks on end.

Since the crew of Chicoutimi was not wearing actigraphs, the submarine surgeon provided estimates of typical submariner sleep behaviour. These sleep behaviour estimates were used in lieu of wrist actigraph data along with crew duty data as inputs to FAST^{TM}. The resulting cognitive effectiveness outputs suggested that the submarine watch schedule(s) result in very significant decreases in cognitive effectiveness. The submarine community therefore tasked DRDC Toronto to conduct a trial on a Canadian submarine (the same class of submarine as HMCS Chicoutimi), this time generating FAST^{TM} models based on real sleep data measured by wrist actigraphs along with daily watch-standing hours to assess the impact of the submarine watch schedule variants for impact on cognitive effectiveness of the crew.

2 Trial Methodology

2.1 Duration of the trial

The Canadian submarine on which this trial took place proceeded on the surface in a relatively relaxed posture (river routine) until submerging 28 hours after departure. Upon submerging, the submarine assumed standard watch routine and remained in this posture until surfacing near Halifax 13 days after departure, and proceeded to her assigned jetty space. The data collection commenced shortly after submerging and lasted for 10 days.

2.2 Subject demographics

The ages of the 21 subjects ranged from 26 to 54 years, with a mean age and standard deviation of 38.6 ±7.6 years. Three of these subjects were non-watch-standers: Commanding Officer (CO), Coxswain (COXSN) and Chief Engine Room Artificer (CERA). The remaining 18 subjects were divided into syndicates of 6 subjects for each of the 1-in-2 back-watch, 1-in-2 front-watch, and 1-in-3 engineering watch.

2.3 Description of watch system variants

Both subsets (i.e., back and front watches) of the 1-in-2 watch system worked 6 hours, were off 6 hours, worked 6 hours and were off again for 6 hours of each 24 hour day. The back-watch duty hours were from 0100 to 0700 hours and from 1300 to 1900 hours for each day at sea. The front-watch duty hours were from 0700 to 1300 hours and from 1900 to 0100 hours. The 1-in-3 engineers' watch is a 3-crew solution in a 3W:0F shift-work system (i.e., a ratio of 3 work days to no days off), with a cycle length of 3 days [6]. The shift plan is the sequence 3-3-4-3-4-3-4, where 3 and 4 are the shift lengths in hours and represent every third sequential shift. The average work demand is 8 hours per day. The actual daily hours worked across the 3-day cycle are 10, 7 and 7, respectively. None of the subjects had any days off work during this trial.

2.4 Data sets collected

In addition to wrist actigraph sleep data and daily watch-standing hours for use in the generation of cognitive effectiveness models with the FAST™ modeling program, the 21 submariners who participated as subjects in this trial made daily inputs into a sleep/activity log. The log had provisions for the recording of daily sleep times (to cover for the possibility of actigraph failure), daily subjective sleep ratings, and daily indices of alertness and mood. The log also had a SOAP (Sustained Operations Assessment Profile) questionnaire [13] which was completed twice during the trial (once at the beginning of the transatlantic passage and once at the end). The SOAP involved subjective assessments of 10 parameters covering three broad areas of functioning including cognitive, affective, and arousal dimensions, such as the ability to concentrate, boredom, performance, anxiety, depression, irritability, fatigue and sleep parameters, work frustration and physical discomfort.

The subjects also performed the PVT which is essentially a reaction time task with a vigilance component in that it is simple, boring and uses randomized inter-stimulus intervals. For the non-watch-standers (CO, COXSN and CERA), twice-daily PVT test times (once in the morning and once in the evening) were targeted. The 1-in-2 watch-standers (both the front and back watch) undertook PVT testing just before reporting for watch and just after completing each watch (i.e., 4 times per day). The 1-in-3 watch-standers undertook PVT testing just before reporting for watch only, i.e., 2 to 3 times per day depending on where they were in the watch system (typically one day of 3 PVT trials, followed by 2 days of 2 trials and then repeating this sequence). Some of the problems with the PVT data collected during this trial make this data set somewhat questionable in terms of data quality. Pipes (boat-wide intercom instructions) that occurred when subjects were performing the PVT distracted them from that task. Sometimes submariners would be carrying on a conversation next to a subject performing the PVT task, and at times, the subject undergoing PVT assessment would be engaged in conversation by shipmates. In many instances, the 1-in-2 and 1-in-3 watch-standers would report for PVT testing having only just arisen from sleep and were suffering from sleep inertia (a transient period of impaired performance upon arising from sleep and which can take from 15 to 45 minutes to resolve). The varying light levels (from almost dark to bright ambient light) in the weapons storage compartment (when the PVT task was performed) can modify performance. Probably the most compelling reason that the PVT data are of questionable utility is that a significant number of subjects were competing for the fast reaction time of the day, every day and this resulted in a shift in the area of the speed-accuracy trade-off curve at which these subjects were choosing to perform. Essentially, for good reaction time data, the subjects should respond as quickly as they can without making mistakes in which case the tolerable error rate is about 2%. However, in their quest for speed, accuracy was sacrificed and many of the subjects had as many errors as correct responses making their data unusable. The PVT data were insufficiently reliable for performance data analysis, although some PVT data files will be used to help further refine the FAST™ model.

2.5 FAST™ Modeling Program

A description of the FAST™ is provided in Annex E. FAST™ graphs are shown in Annex A for the non-watch-standers, Annex B for the 1-in-2 back-watch-standers, Annex C for the 1-in-2 front-watch-standers, and Annex D for the 1-in-3 watch-standers. Some details regarding these graphs are as follows:

- The vertical axis on the left side of the FAST™ graphs represents human cognitive performance effectiveness as a percentage of optimal performance (100%). The oscillating line in the diagram represents average performance (cognitive effectiveness) as determined by time of day, biological rhythms, time spent awake, and amount of sleep.

- The dotted line which is below the cognitive effectiveness curve and follows a similar oscillating pattern as the cognitive effectiveness represents the 10th percentile of cognitive effectiveness.

- The green band (from 90% to 100%) represents acceptable cognitive performance effectiveness for workers conducting safety sensitive jobs (flying, driving, weapons operation, command and control, etc.).

- The yellow performance band (from 65% to 90% cognitive effectiveness) indicates caution. Personnel engaged in skilled performance activities such as aviation should not be allowed to operate in this performance band.

- The area from the dotted line to the pink area represents the cognitive effectiveness equivalent to the circadian nadir and a 2nd day without sleep.

- The pink performance band (below 65%) represents performance effectiveness after 2 days and a night of sleep deprivation. Under these conditions, no one can be expected to function well on any task.

- The vertical axis on the right side of FAST™ graphs represents the Blood Alcohol Content (BAC) equivalency throughout the spectrum of cognitive effectiveness. A value of 77% cognitive effectiveness corresponds to a blood alcohol content of 0.05% (legally impaired in some jurisdictions). A value of 70% cognitive effectiveness corresponds to a blood alcohol content of 0.08% (legally impaired in most jurisdictions). These BAC equivalency levels associated with sleep deprivation/fatigue are based on three important studies [1, 4, 5].

- The abscissa (x-axis) illustrates periods of work (red bars), sleep (blue bars), darkness (gray bars) and time of day in hours

- The red triangles labelled C1 and C2 and located just above the abscissa are event markers indicating when the submarine left port (1100 hours Zulu time) and when the submarine submerged and regular watches began (1700 hours Zulu time on June 27, 2007)

2.6   Statistical analysis of subjective data

2.6.1   Sleep ratings

Each day, on a scale of 1 to 5, the subjects were asked to rate their difficulty falling asleep, their depth of sleep, their difficulty arising from sleep, and how rested they felt after sleep. Such 'interval data' is not normally distributed and is therefore analysed via non-parametric statistics. The Kruskal-Wallis analysis was used to assess group differences, and the Friedman Analysis of Variance (ANOVA) to test repeated measures across days. The Wilcoxon test was also used to assess matched pairs of cells.

2.6.2   Visual Analog Scale (VAS) ratings

The daily visual analog scales (VAS) tracked the following 8 parameters: alertness, sadness, tension, effort, happiness, weariness, calmness, and sleepiness. The subjects were presented with a 100 mm line for each parameter and were asked to indicate their subjective assessments related to each parameter by making a small vertical mark through the appropriate point of the line. The point at which the vertical mark was made in the line was measured and recorded. For example, a mark at 85 mm from the left-hand end of the line would yield a score of 85. Since these data are from a continuous scale (i.e., from 0 to 100) they were considered to be normally distributed and thus analysed by standard parametric means. A split-plot ANOVA with 3 between factors (i.e. 3 different watch system variants) and 12 repeated measures (i.e. 12 days at sea) was used for analysis of the VAS data.

2.6.3 SOAP ratings

Similar to the subjective sleep ratings, the SOAP profile was completed twice (once at the beginning of the trip and once at the end of the trip). Similar to the subjective sleep assessments, the subjects were asked to rate their SOAP assessments (measures of concentration, boredom, slowed reactions, anxiety, depression, irritability, fatigue, poor sleep, work frustration, and physical discomfort) on a scale of 1 to 5. Each of these 10 parameters included 9 sub-parameters, each of which could be scored as 1 to 5. Therefore, the composite score for each parameter (e.g., concentration) could range from 9 (if each sub-parameter was scored as a '1') to 45 (if each parameter was scored as a '9'). Since these 'interval data' are not normally distributed they were analysed with the same non-parametric methods as the subjective sleep ratings; i.e., Kruskal-Wallis analysis to assess group differences, Friedman ANOVA to assess the 2 levels of repeated measures (pre-trip versus post-trip), and the Wilcoxon test to assess matched pairs of cells.

2.6.4 Statistical Power

For a significance level of $p = 0.10$ (which is appropriate for field studies), and with $n = 6$ (i.e., 6 subjects in each of the 1-in-2 back-watch, 1-in-2 front-watch, and 1-in-3 engineers' watch groups), and for an effect size of 1 standard deviation and test- retest reliability in repeated measures of $r = 0.5$, the power of this design is 74% [3].

3 Results

3.1 Cognitive effectiveness of the Non-Watch-Standers

The FAST^{TM} models representing the predicted cognitive effectiveness of the 3 non-watch-standing subjects are illustrated in Annex A. To show how cognitive effectiveness changes over time at sea, the mean daily duty cognitive effectiveness of these individuals is illustrated in Table 1.

Table 1 Cognitive effectiveness of non-watch-standers during transatlantic passage to Halifax

Subject	Daily Mean duty % cognitive effectiveness										
	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
CO	85	81	78	77	77	75	79	79	77	79	80
COXSN	87	83	85	87	83	89	78	89	83	83	83
CERA	71	58	55	43	50	36	36	31	31	31	31

77.5 % cognitive effectiveness equates to blood alcohol content of 0.05%
70 % cognitive effectiveness equates to a blood alcohol content of 0.08%

(yellow) = 0.05% or higher blood alcohol content equivalent
(red) = 0.08% or higher blood alcohol content equivalent

The extremely low levels of the CERA's cognitive effectiveness are directly attributable to his very poor sleep quality (reported with the CERA's permission). His average sleep latency (the time required to fall asleep after getting into bed) was quite long: 60 minutes. His average total time spent awake during each sleep period after initial sleep onset was excessive at 82 minutes, and his sleep efficiency was only 50% (i.e., for each sleep period, on average he spent only 50% of his time asleep).

3.2 Cognitive effectiveness of the 1-in-2 Back-Watch-Standers

The FAST^{TM} models representing the predicted cognitive effectiveness of the back-watch-standers are illustrated in Annex B. To show how cognitive effectiveness changes over time at sea, the mean daily duty cognitive effectiveness of these individuals is illustrated in Table 2.

Table 2 Cognitive effectiveness of 1-in-2 back-watch-standers during transatlantic to Halifax

| Subject I.D. # | Shift time | Daily Mean duty % cognitive effectiveness | | | | | | | | | | |
		Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
4*	01-07 h	71	69	62	62	59	61	55	46	46	41	45
5	01-07 h	82	82	69	79	66	67	64	67	59	64	59
6	01-07 h	83	78	76	72	68	67	66	63	61	65	60
7	01-07 h	Subject 7 cognitive effectiveness not available - actigraph failure										
8	01-07 h	78	74	70	69	66	66	63	61	45	56	56
9	01-07 h	71	71	70	69	61	65	64	67	66	64	64
4*	13-19 h	84	77	75	68	68	67	58	56	58	56	58
5	13-19 h	92	86	80	82	81	78	76	77	77	74	74
6	13-19 h	88	84	83	80	80	80	76	75	77	74	76
7	13-19 h	Subject 7 cognitive effectiveness not available - actigraph failure										
8	13-19 h	74	70	69	77	74	73	75	70	73	61	70
9	13-19 h	75	76	77	76	79	75	76	78	75	79	76

* = watch leader

77.5 % cognitive effectiveness equates to blood alcohol content of 0.05%
70 % cognitive effectiveness equates to a blood alcohol content of 0.08%

(yellow) = 0.05% or higher blood alcohol content equivalent
(red) = 0.08% or higher blood alcohol content equivalent

Mean and minimum cognitive effectiveness for both of the 1-in-2 back-watch periods are illustrated in Figure 1. Note the accumulation of fatigue across days at sea due, presumably, to inadequate sleep quality and/or quantity. Cumulative fatigue builds up across major waking periods when there is inadequate recovery (due to inadequate sleep) between the waking periods. Recovery from cumulative fatigue cannot be accomplished in one good-quality, nocturnal sleep period. One very important aspect of cumulative fatigue is sleep debt.

Figure 1 Mean and minimum cognitive effectiveness over days at sea for both of the 1-in-2 back watch periods. Solid circles and squares are mean values ± s.e.m. and open circles and squares are minimum values ± s.e.m.

3.3 Cognitive effectiveness of the 1-in-2 Front-Watch-Standers

The FAST[TM] models representing the predicted cognitive effectiveness of the front-watch-standers are illustrated in Annex C. To show how cognitive effectiveness changed over time, the mean daily duty cognitive effectiveness of these individuals is illustrated in Table 3.

Table 3 Cognitive effectiveness of 1-in-2 front-watch-standers during transatlantic to Halifax

Subject I.D. #	Shift time	Daily Mean duty % cognitive effectiveness										
		Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	Day 8	Day 9	Day 10	Day 11	Day 12
10*	07-13 h	84	79	73	72	70	73	73	70	68	70	72
11	07-13 h	89	85	79	76	70	72	74	73	73	74	73
12	07-13 h	85	79	75	72	68	71	69	68	67	70	68
13	07-13 h	86	82	80	78	72	72	72	73	70	71	65
14	07-13 h	87	81	77	74	77	73	76	73	75	73	68
15	07-13 h	82	81	83	82	73	77	79	78	77	72	73
10*	19-01 h	67	61	53	46	47	55	53	52	45	49	48
11	19-01 h	74	69	59	56	53	53	52	51	52	54	51
12	19-01 h	67	59	51	48	49	50	48	46	47	54	51
13	19-01 h	67	62	60	56	57	52	48	49	53	54	49
14	19-01 h	72	60	54	50	56	51	57	58	57	53	52
15	19-01 h	68	64	x	x	54	56	61	59	56	49	53

* = watch leader

x = Subject 15 not on evening watch on Days 4 and 5

77.5 % cognitive effectiveness equates to blood alcohol content of 0.05%

70 % cognitive effectiveness equates to a blood alcohol content of 0.08%

(yellow) = 0.05% or higher blood alcohol content equivalent

(red) = 0.08% or higher blood alcohol content equivalent

Mean and minimum cognitive effectiveness for both of the 1-in-2 front-watch periods are illustrated in Figure 2. Note the decline in effectiveness over days at sea. The rate of decline is somewhat less than for the back watch (Figure 1).
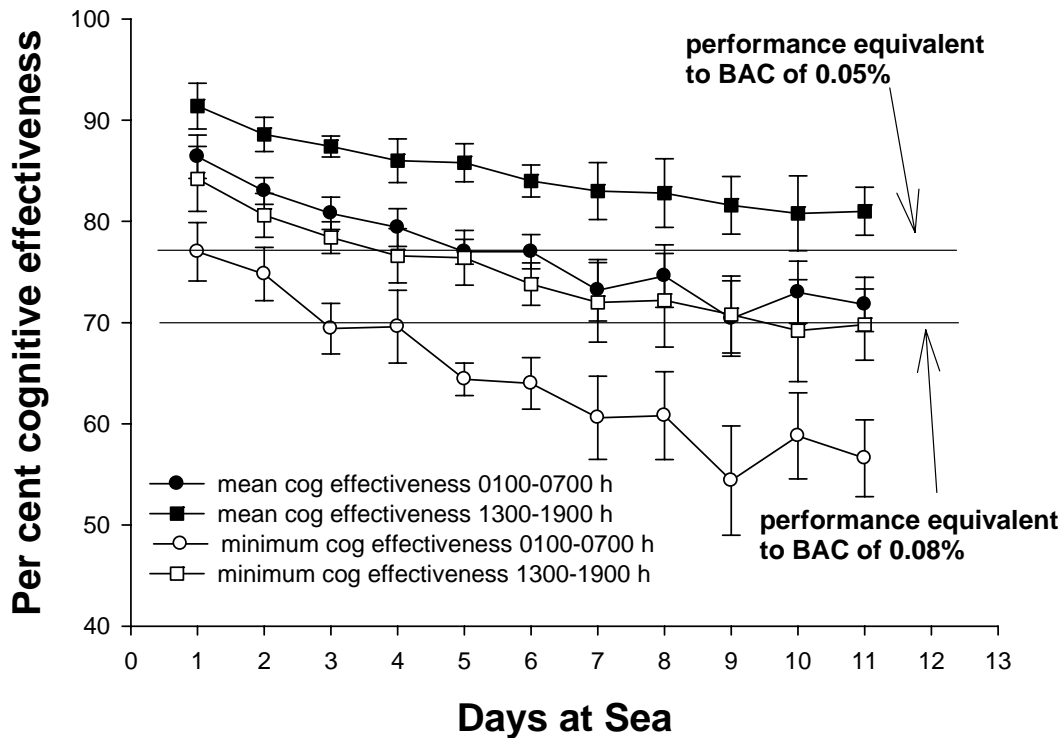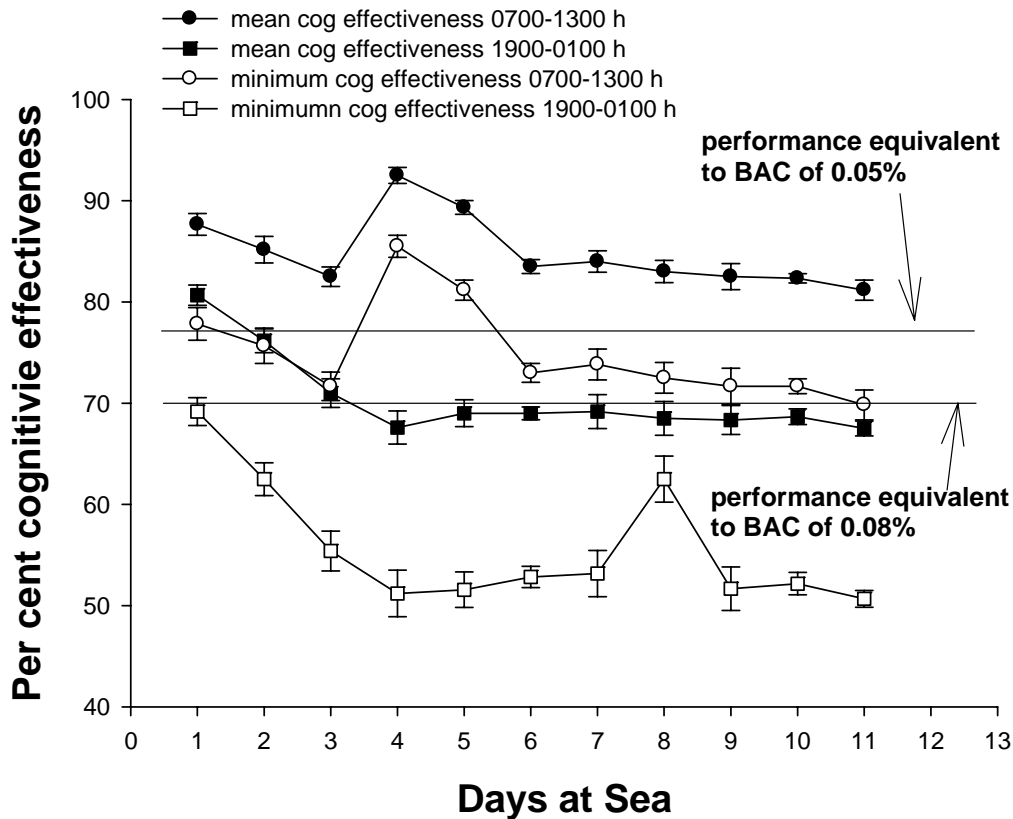
Figure 2. Mean and mimimum cognitive effectiveness over days at sea for both of the 1-in-2 front watch periods. Solid circles and squares are mean values ± s.e.m. and open circles and squares are minimum values ± s.e.m.

3.4   Cognitive effectiveness of the 1-in-3 Engineering-Watch-Standers

The FAST[TM] models representing the predicted cognitive effectiveness of the 1-in-3 engineering-watch-standers are illustrated in Annex D. The mean individual cognitive effectiveness at the middle of each watch period is illustrated in Table 4.

Table 4 Cognitive effectiveness of 1-in-3 engineers' watch-standers at middle of each of 7 watch periods during transatlantic passage to Halifax

Subject	Daily Mean % cognitive effectiveness at middle of each watch period						
	07-10 h	10-13 h	13-16 h	16-19 h	19-23 h	23-03 h	03-07 h
16	85	84	88	85	74	73	81
17	85	78	89	87	68	78	85
18	96	93	96	98	84	80	88
19	89	90	95	89	76	79	84
20	83	84	89	85	70	70	80
21	84	82	86	83	69	71	82

77.5 % cognitive effectiveness equates to blood alcohol content of 0.05%
70 % cognitive effectiveness equates to a blood alcohol content of 0.08%

(yellow) = 0.05% or higher blood alcohol content equivalent
(red) = 0.08% or higher blood alcohol content equivalent

To show how cognitive effectiveness changed over time at sea for the 1-in-3 engineers' watch group of subjects, the group mean cognitive effectiveness for each watch period is illustrated over time (i.e., over subsequent watch iterations) in Table 5. The elapsed time between iterations of the same watch period is 2 days. However, since these 1-in-3 watch-standers are distributed between red, white, and blue watches, the dates these watches were stood at sea (and therefore the actual number of watches stood at sea) varies between the red, white and blue watches in this 1-in-3 watch system.

Table 5 Mean cognitive effectiveness of 1-in-3 engineers' watch-standers over trials for each of 7 watch periods during transatlantic passage to Halifax

Watch period	Mean group % cognitive effectiveness for each watch iteration			
	1st	2nd	3rd	4th
0700-1000 h	92.2	87.8	84.2	83.3
1000-1300 h	89.7	87.3	73.8	84.7
1300-1600 h	94.0	91.8	87.2	88.0
1600-1900 h	90.3	88.8	86.0	85.7
1900-2300 h	74.7	73.8	68.7	69.5
2300-0300 h	80.5	75.3	69.2	75.0
0300-0700	88.7	84.5	79.2	71.0

77.5 % cognitive effectiveness equates to blood alcohol content of 0.05%
70 % cognitive effectiveness equates to a blood alcohol content of 0.08%

(yellow) = 0.05% or higher blood alcohol content equivalent
(red) = 0.08% or higher blood alcohol content equivalent

Mean and minimum cognitive effectiveness for each of the seven 1-in-3 front-watch periods are illustrated in Figure 3.

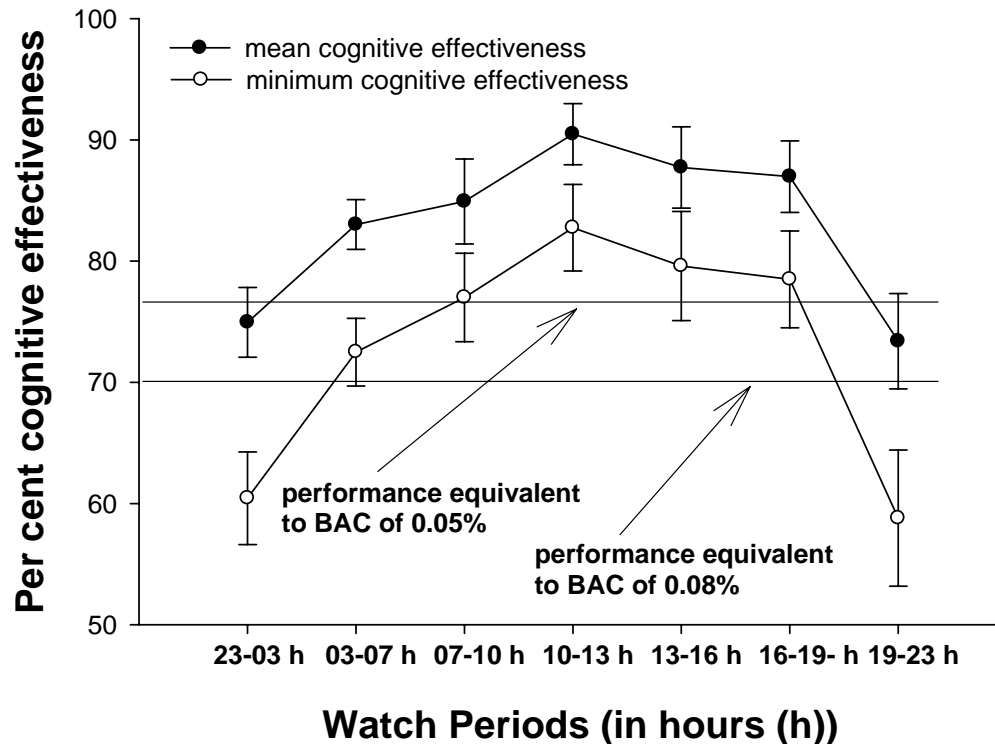*Figure 3. Mean and minimum cognitive effectiveness for each of the seven 1-in-3 watch periods. Solid circles are mean values ± s.e.m. and open circles are minimum values ± s.e.m.*

3.5 Subjective sleep/activity log data

Since there were only 3 non-watch-stander subjects and one of those subjects was obviously suffering from a form of sleep pathology as evidenced by his actigraphic data, the non-watch standers are nor represented in any of the 3 subjective data sets (sleep ratings, visual analogue mood ratings, and SOAP ratings).

3.5.1 Sleep ratings

On a scale of 1 to 5, the subjects were asked to rate their difficulty falling asleep, their depth of sleep, their difficulty arising from sleep, and how rested they felt after sleep.

The data reflecting 'difficulty getting to sleep' are illustrated in Figures 4 and 5.

Figure 4. Mean 'difficulty getting to sleep' between watch types (1-in-2 back watch, 1-in-2 front watch, 1-in-3 engineers' watch) over days at sea. All values are mean ± s.e.m.

The Kruskal-Wallis test for difficulty getting to sleep confirmed that there were no differences between groups (Chi-square = .6428571, df = 2, p=0.725). The Friedman ANOVA (Chi-square (N=18, df=11) = 19.89, p=0.047 indicates that 'difficulty getting to sleep changed over days at sea. To better illustrate this main effect of days at sea on 'difficulty getting to sleep', Figure 4 is collapsed over groups and re-plotted as Figure 5.
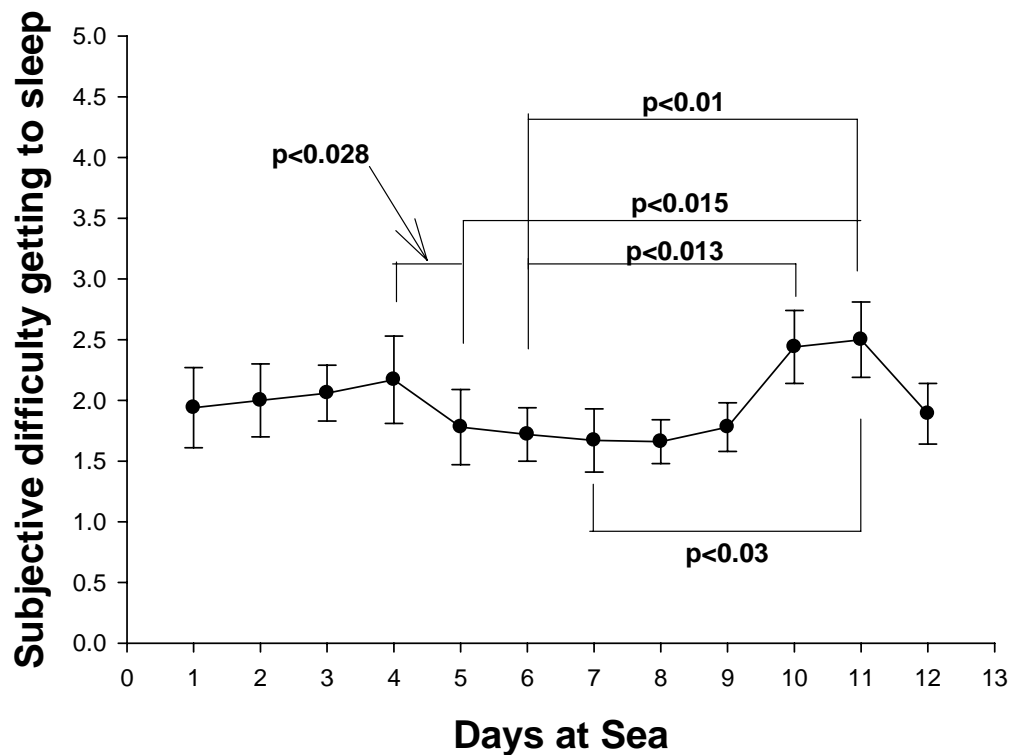
Figure 5. Mean 'difficulty getting to sleep' over days at sea. All values are mean ± s.e.m.

Post hoc analysis of Figure 5 using the Wilcoxon matched pairs test indicates that 'difficulty getting to sleep fell slightly on Day 5, relative to the first 4 days, and remained relatively stable for the next 5 days, before climbing again on Days 10 and 11.

3.5.1.1 'Depth of Sleep'

The data illustrating the 'depth of sleep' is shown in Figure 6. The Kruskal-Wallis test for difficulty getting to sleep confirmed there were no differences between groups (Chi-square = .000000, df = 2, p=1.000). The Friedman ANOVA (Chi-square (N=18, df=11) = 17.18052, p=.10265 indicated that there were no changes in 'depth of sleep' over days at sea.

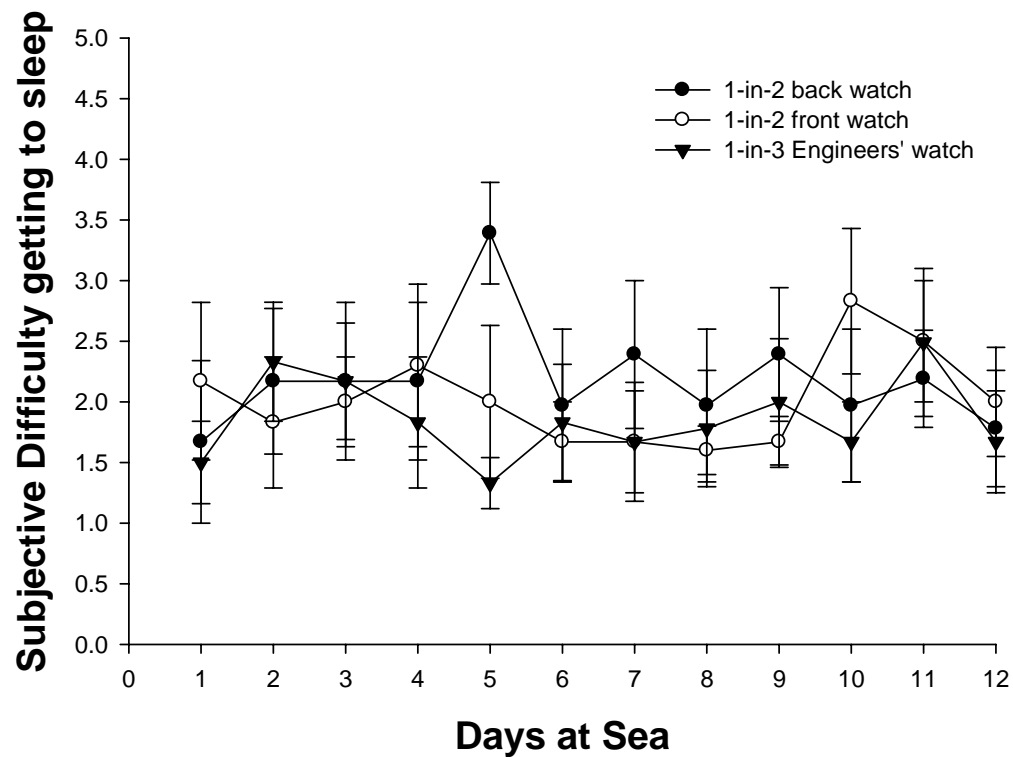*Figure 6. Mean 'depth of sleep' beween watch types (1-in-2 back watch, 1-in-2 front watch, 1-in-3 engineers' watch) over days at sea. All values are mean ± s.e.m.*

3.5.1.2   'Difficulty arising from sleep'

The data reflecting 'difficulty arising from sleep' is illustrated in Figures 7 and 8. The Kruskal-Wallis test for 'difficulty arising from sleep' confirmed there were no differences between groups (Chi-square = .5538462, df = 2, p= .7581). The Friedman ANOVA (Chi-square (N=18, df=11) = 37.82991, p= .00008 indicated that 'depth of sleep' changed over days at sea. To better illustrate this main effect of days at sea on 'difficulty arising from sleep', Figure 7 is collapsed over groups and re-plotted as Figure 8.

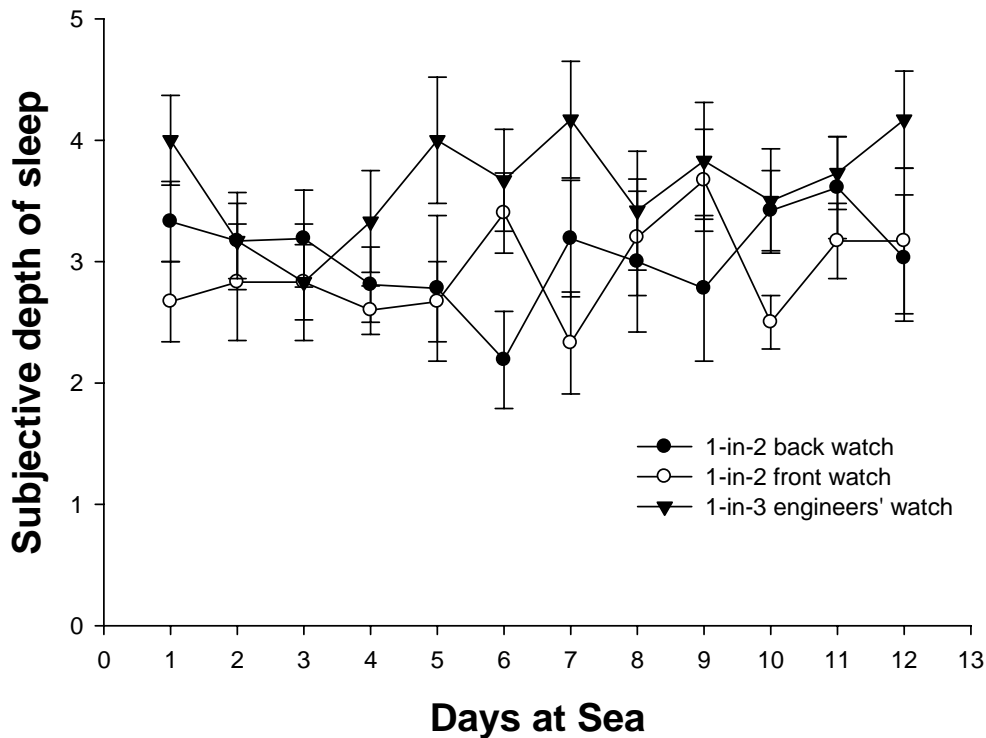*Figure 7. Mean 'difficulty arising from sleep' between watch types (1-in2 back watch, 1-in-2 front watch, 1-in-3 engineers' watch) over days at sea. All values are mean ± s.e.m.*

The Wilcoxon matched pairs test was used for post hoc analysis of the main effect of days at sea for 'difficulty arising from sleep'. The appropriate 'p values' comparing the various days at sea for 'difficulty arising from sleep' are illustrated in Figure 8. These 'p values' indicate that difficulty arising from sleep generally increases from Day 1 to Day 9 and then falls slightly on Day 10 and by Day 11 reaches parity with Day 1, before increasing again on Day 12. The gradual increase across days at sea indicates accumulating fatigue.
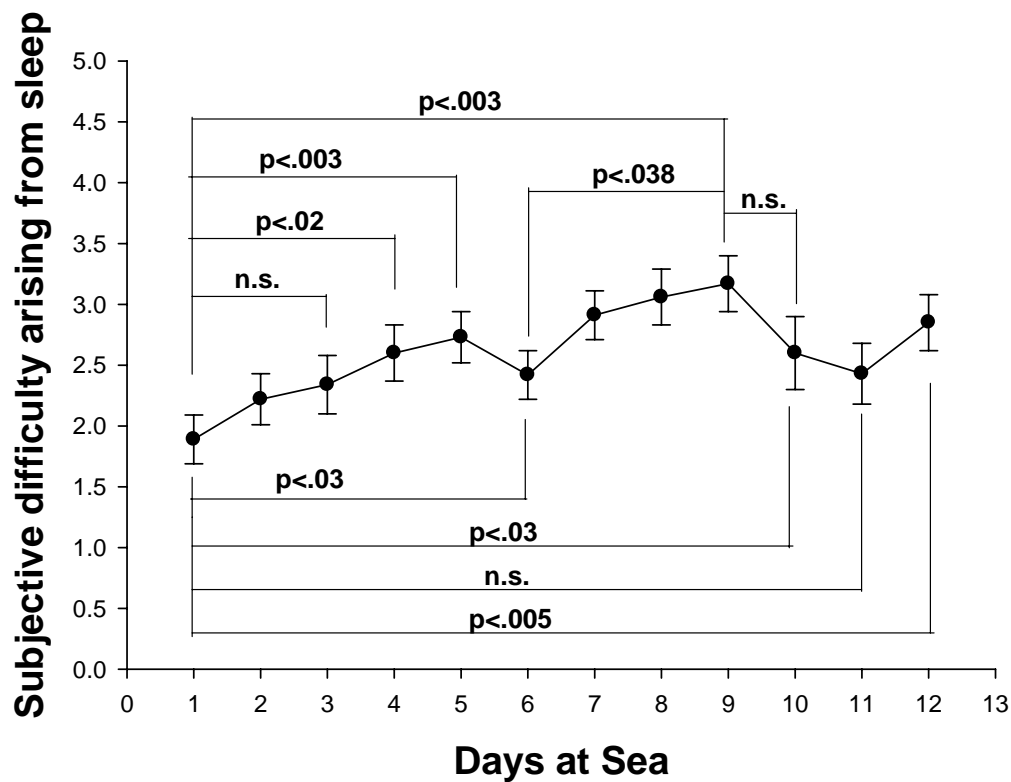
Figure 8. Mean 'difficulty arising from sleep' over days at sea. All values are mean ± s.e.m.

3.5.1.3 'Restedness upon arising from sleep'

The data reflecting 'restedness upon arising from sleep' is illustrated in Figures 9 and 10. The Kruskal-Wallis test confirmed there were no group differences in 'difficulty arising from sleep' groups (Chi-square = .000000, df = 2, p= 1.000). The Friedman ANOVA (Chi-square (N=18, df=11) = 36.08612, p= .00016 indicated that 'restedness upon arising from sleep' changed over days at sea. To better illustrate this main effect of days at sea on 'restedness upon arising from sleep', Figure 9 is collapsed over groups and re-plotted as Figure 10.
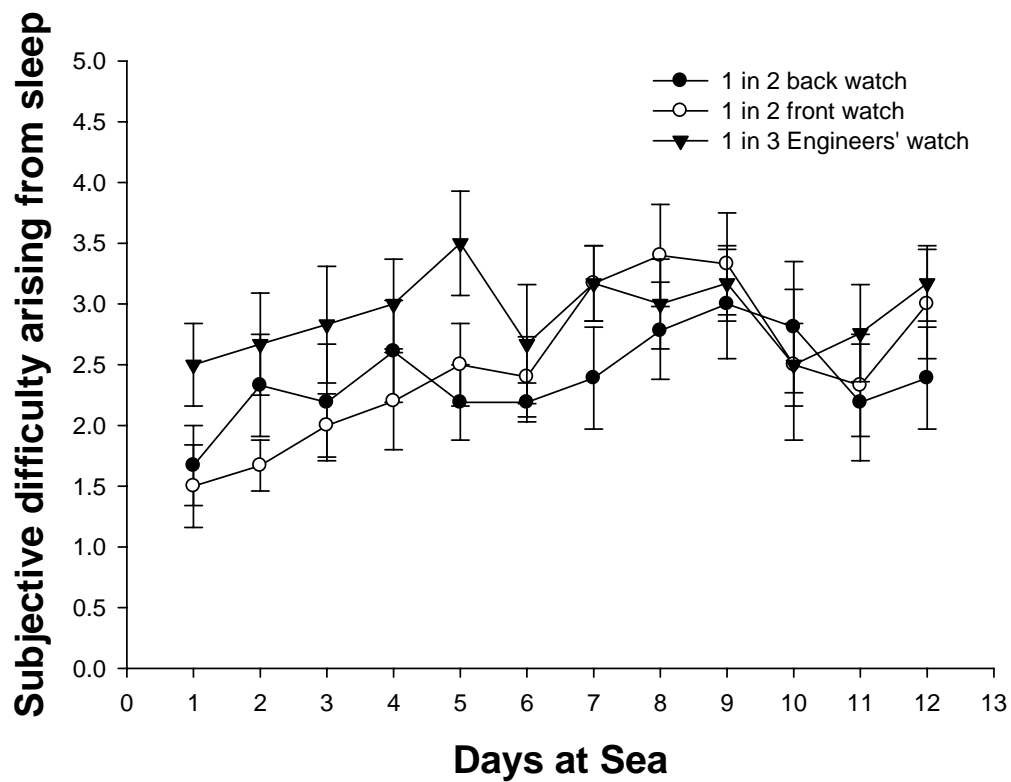
Figure 9. Mean level of 'restedness upon arising from sleep' between watch types (1-in-2 back watch, 1-in-2 front watch, 1-in-3 engineers' watch) over days at sea. All values are mean ± s.e.m.
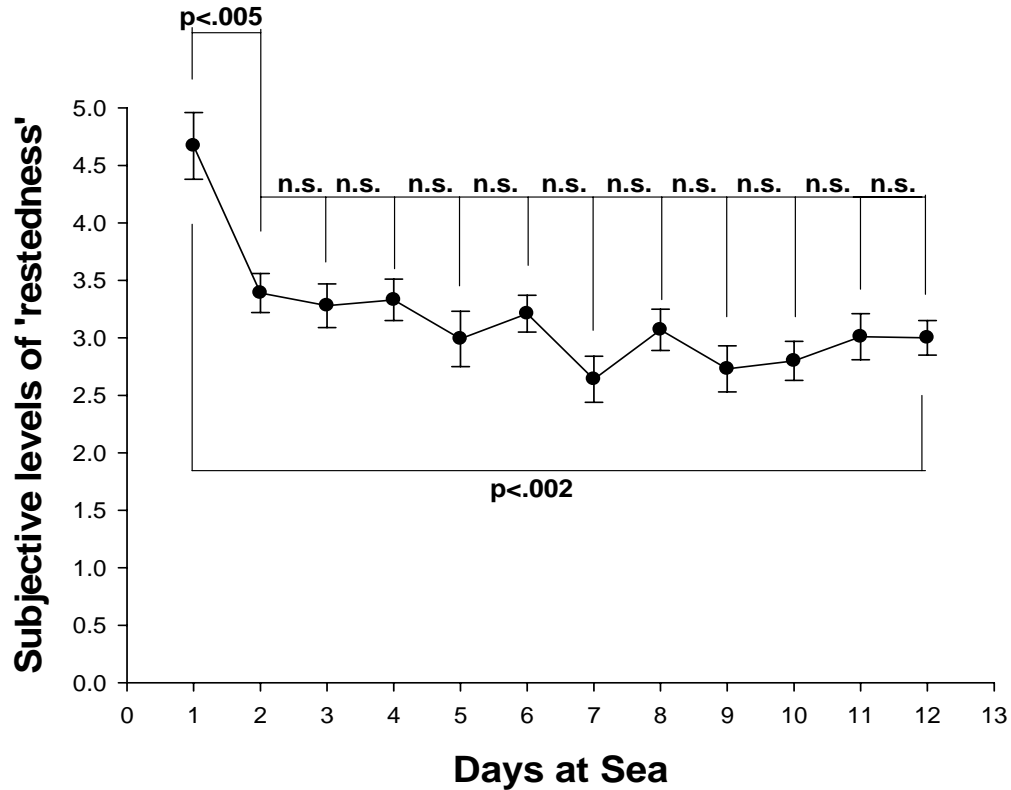
Figure 10. Mean level of 'restedness upon arising from sleep' over days at sea. All values are mean ± s.e.m.
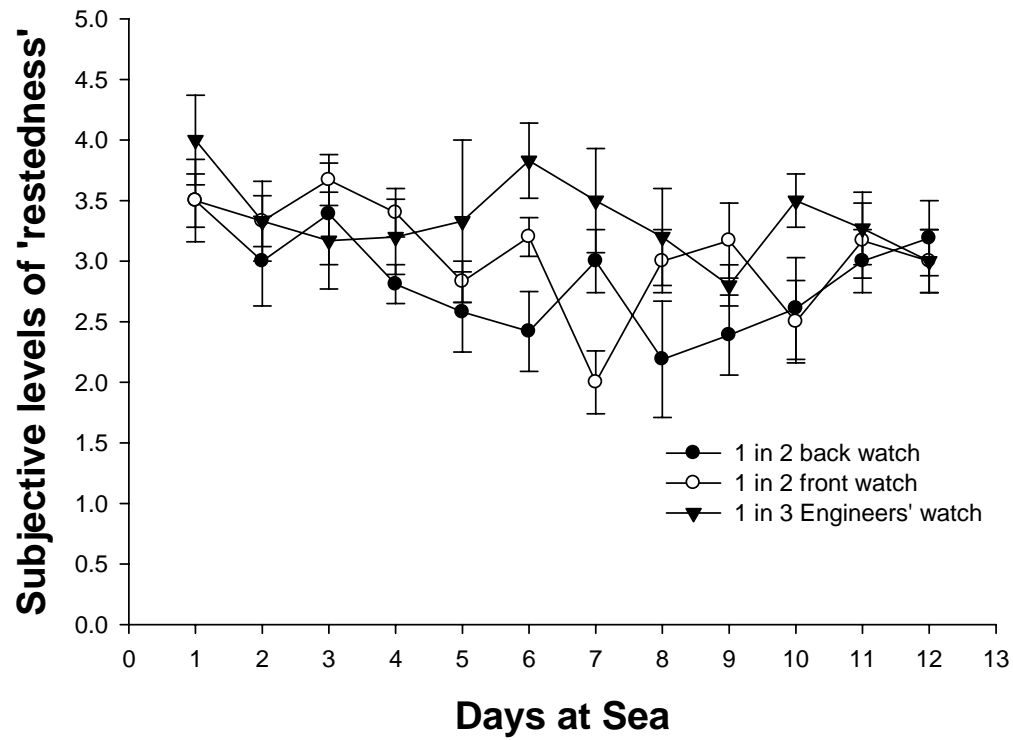
The Wilcoxon matched pairs test was used for post hoc analysis of the main effect of days at sea to assess day to day changes in 'restedness upon awakening from sleep'. The appropriate 'p values' comparing the various days at sea for 'difficulty arising from sleep' are illustrated in Figure 10. These 'p values' indicate that level of 'restedness' increased significantly from Day 1 to Day 2 and remained at Day 2 levels until the end of the trial.

3.5.2   VAS Ratings

The daily VAS ratings tracked the following 8 parameters; alertness, sadness, tension, effort, happiness, weariness, calmness, and sleepiness. Of the 8 parameters, only alertness and happiness showed any differences between groups or changes over days at sea. While alertness and happiness data will be demonstrated, sleepiness data will also be illustrated to show that there were no significant differences between watches or changes over days at sea. Subjects were consistently at elevated levels of sleepiness throughout their time at sea.

3.5.2.1 Alertness

The alertness data are illustrated in Figures 11 and 12. The 3 watch types x 12 days at sea ANOVA indicated that the main effect of watch type $F_{(2,15)} = 1.2885$, $p<.30$ was not significant, the main effect of days at sea $F_{(11,165)} = 2.8752$, $p<.002$ was significant, and the watch type x days at sea interaction $F_{(22, 165)} = .598$, $p<.92$ was not significant.

Figure 11. Mean level of alertness between watch types (1-in-2 back watch, 1-in-2 front watch, 1-in-3 engineers' watch) over days at sea. All values are mean ± s.e.m.

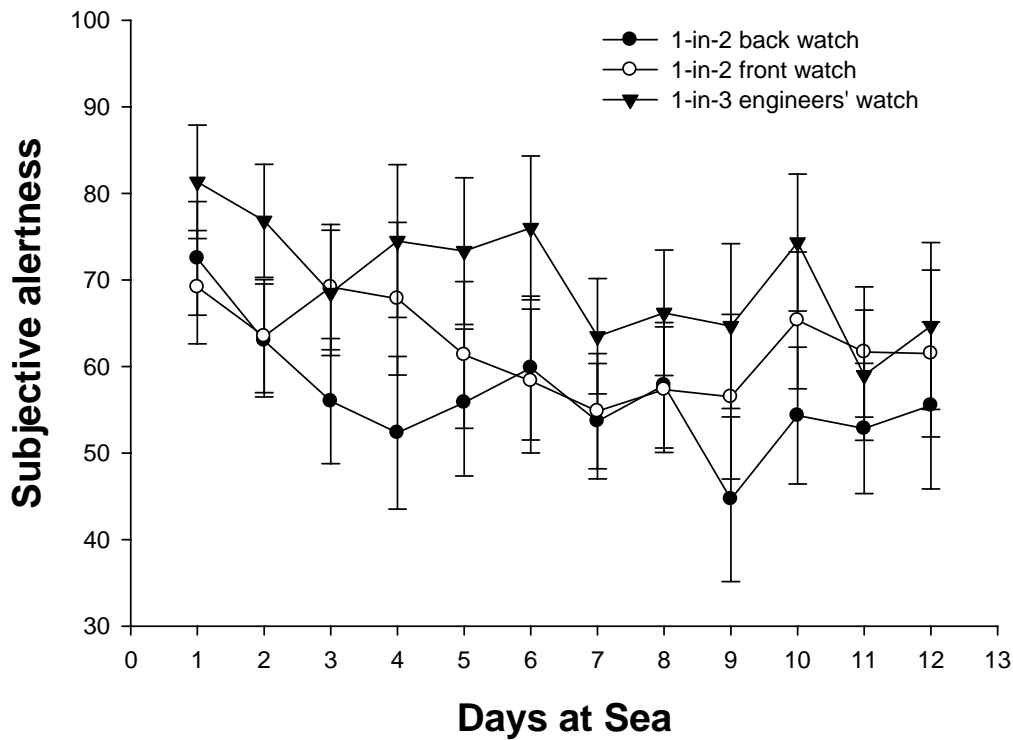To better illustrate the main effect of days at sea Figure 11 is collapsed over watch types and is re-plotted as Figure 12.
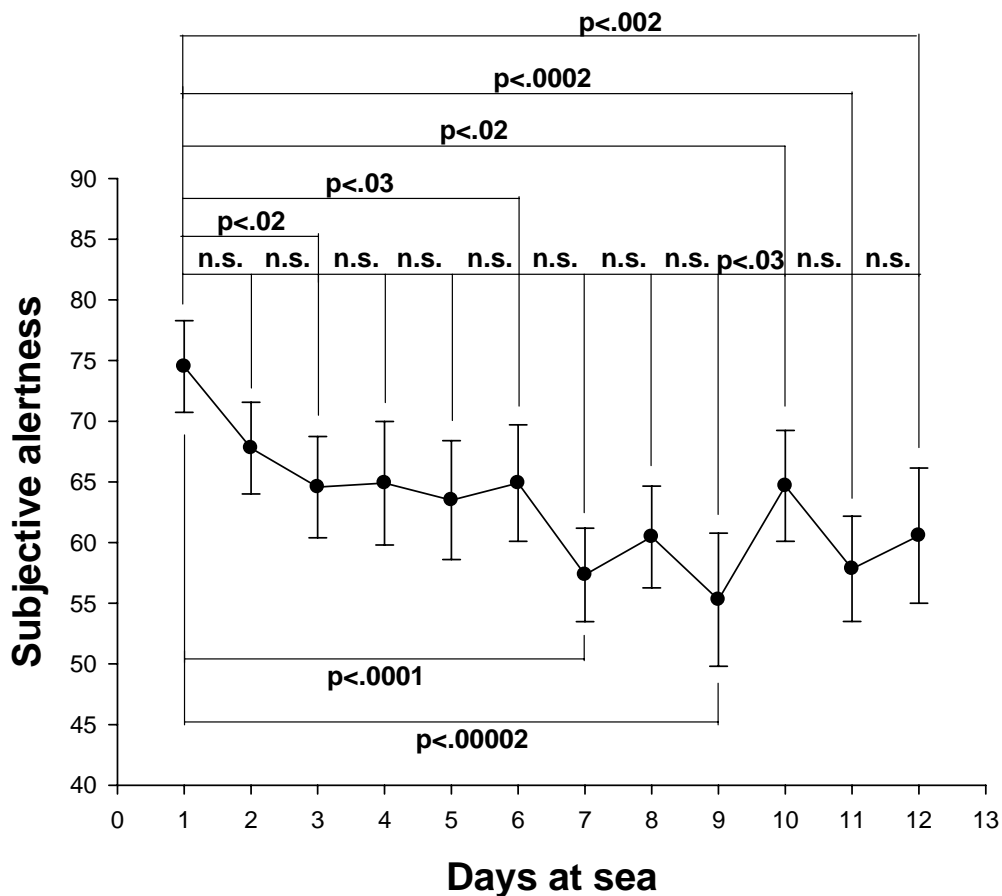
Figure 12. Degradation of alertness over days at sea. All values are mean ± s.e.m.

The Least Significant Difference (LSD) test was used for post hoc analysis of the main effect of days at sea to assess day to day changes in alertness. The appropriate 'p values' comparing the various days at sea for 'alertness' are illustrated in Figure 12 and indicate that level of 'alertness' degrades progressively across days at sea, reflecting accumulating fatigue.

3.5.2.2   Happiness

The happiness data are illustrated in Figures 13 and 14. The 3 watch types x 12 days at sea ANOVA indicates that the main effect of watch type $F_{(2,15)} = 4.1277$, $p < .037$ was significant, the main effect of days at sea $F_{(11,165)} = 1.1287$, $p < .342$ was not significant, and the watch type x days at sea interaction $F_{(22, 165)} = 1.399$, $p < .121$ was not significant.

Figure 13. Mean level of 'happiness' between watch types (1-in-2 back watch, 1-in-2 front watch, 1-in-3 engineers' watch) over days at sea. All values are mean ± s.e.m.

To illustrate the significant effect of watch type on happiness, Figure 13 is collapsed over days and is re-plotted in Figure 14.
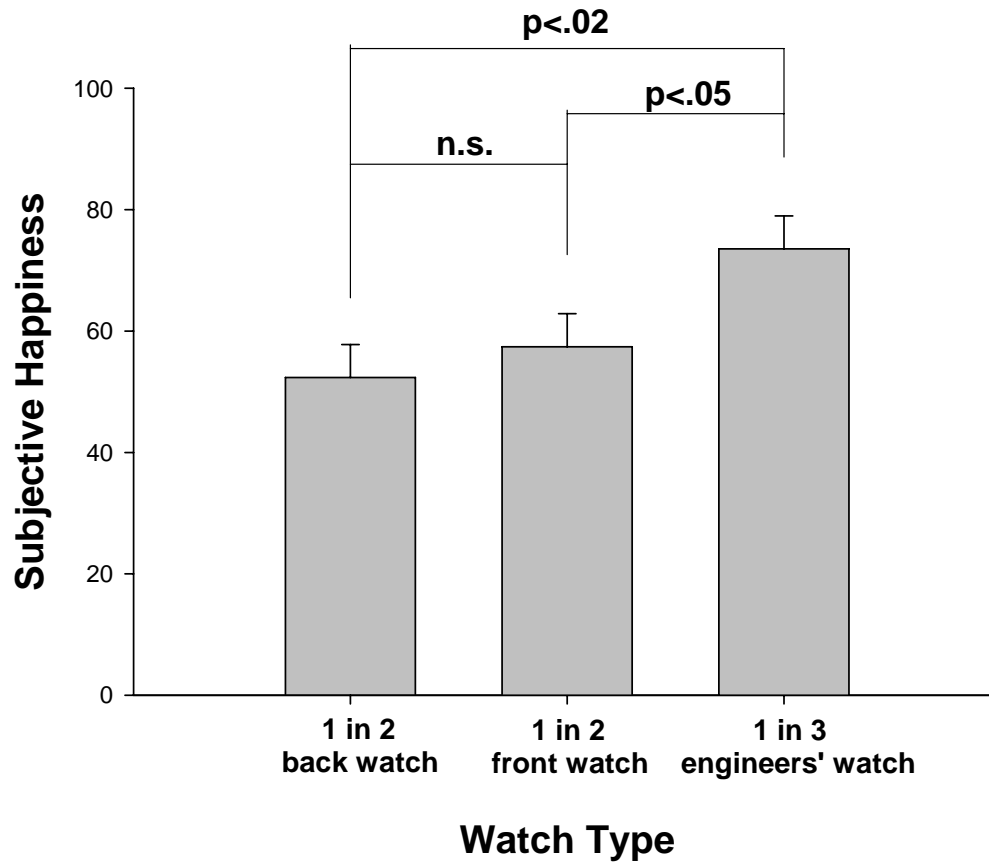
Figure 14. Mean levels of 'happiness' as a function of watch type. All values are mean ± s.e.m.

The LSD test was used for post hoc analysis of the main effect of watch type on happiness. The appropriate 'p values' comparing the 3 watch types for 'happiness' are illustrated in Figure 14 and indicate that the 1-in-3 engineering-watch-standers were happier than both groups of the 1-in-2 front and back-watch-standers.

3.5.2.3   Sleepiness

The sleepiness data are illustrated in Figure 15. The 3 watch types x 12 days at sea ANOVA indicated that the main effect of watch type $F_{(2,15)} = 1.0921$, $p<.037$ was not significant, the main effect of days at sea $F_{(11,165)} = 1.0457$, $p<.409$ was not significant, and the watch type x days at sea interaction $F_{(22, 165)} = .8212$, $p<.696$ is not significant. Essentially, there were no significant differences in sleepiness between watch types, and there were no significant changes in sleepiness over days at sea. However, a look at Figure 15, will confirm that the entire subject population reported sleepiness in the middle of the sleepiness scale thus confirming that they

were quite sleepy. This is not surprising given the demands of the three submarine watch schedule variants.
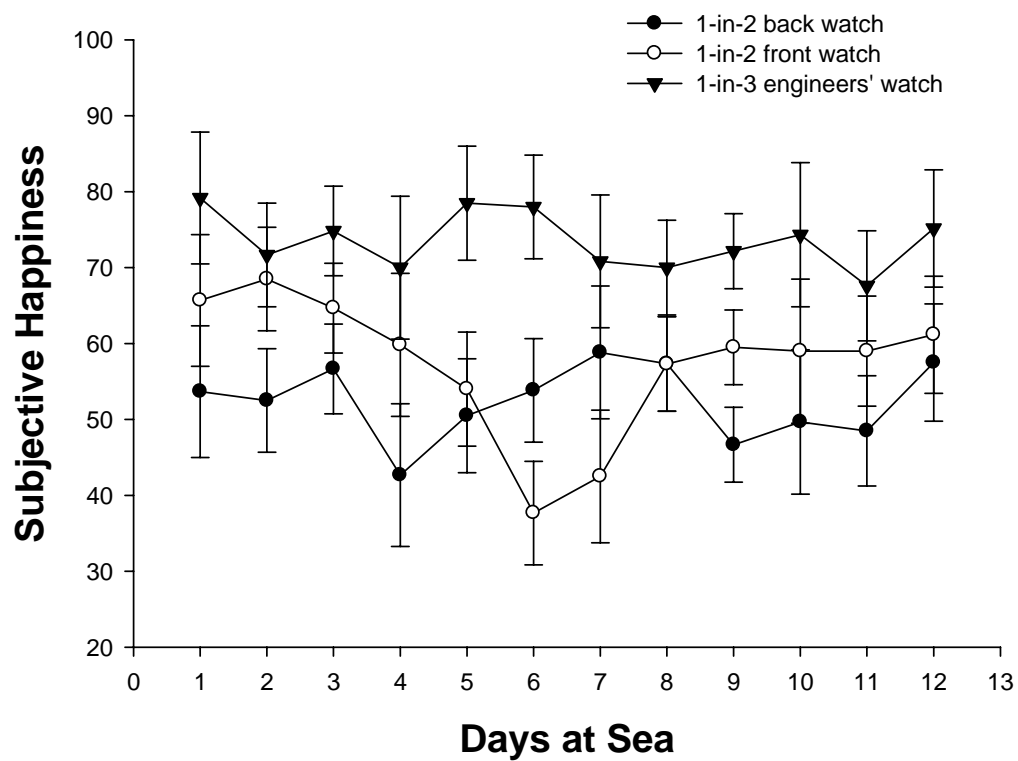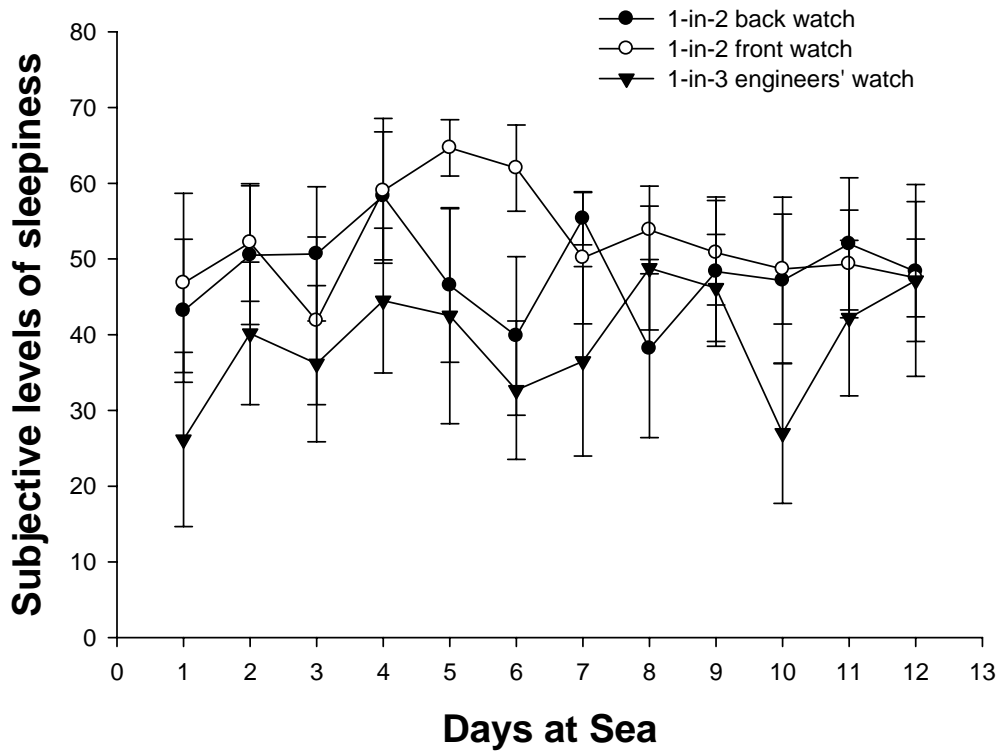

Figure 15. Mean 'level of sleepiness' between watch types (1-in-2 back watch, 1-in-2 front watch, 1-in-3 engineers' watch) over days at sea. All values are mean ± s.e.m.

3.5.3 SOAP Ratings

The composite score for each of the 10 parameters (measures of concentration, boredom, slowed reactions, anxiety, depression, irritability, fatigue, poor sleep, work frustration, and physical discomfort) is illustrated in Figure 16.

DRDC TR 2008-007
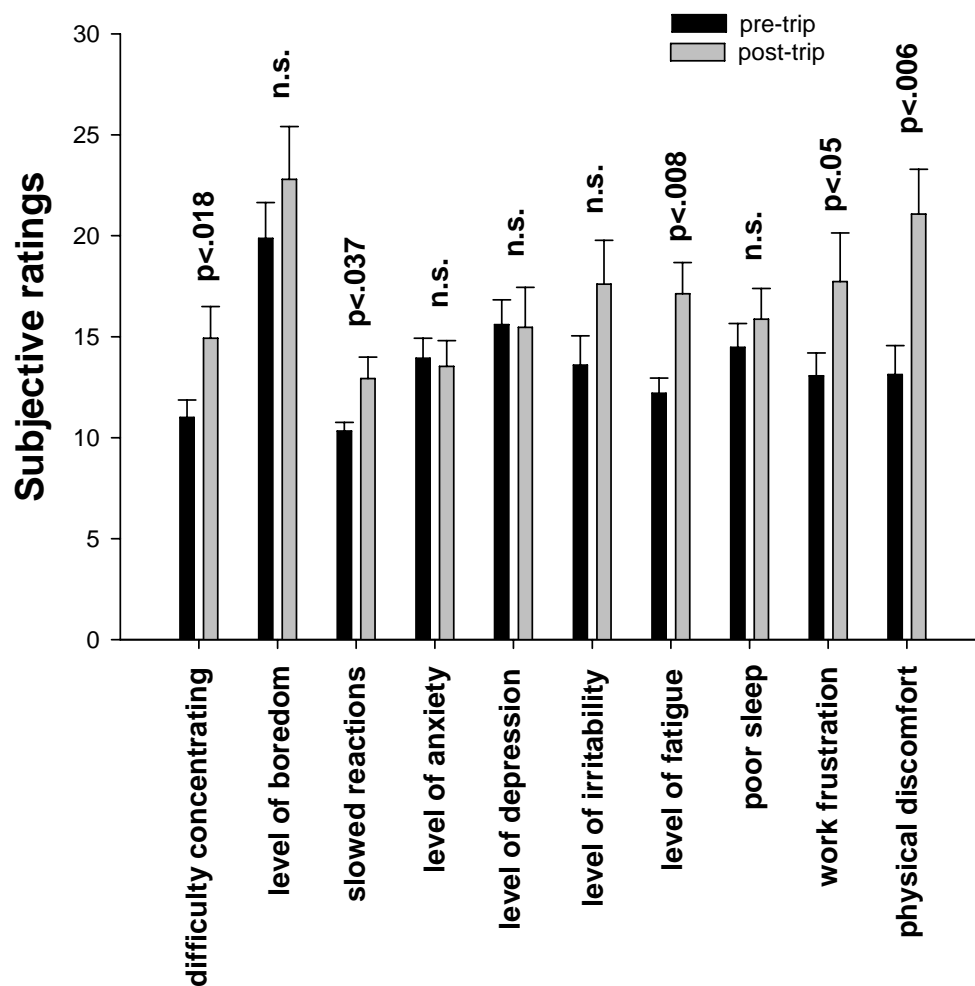
Figure 16. Mean levels of each of 10 SOAP parameters pre- and post-trip collapsed over the 3 watch system variants. All values are ± s.e.m.

The data from Subjects 10 (watch leader 1-in-2 front watch) 16 and 17 (both 1-in-3 engineers' watch standers) are not included in these analyses since they did not complete the SOAP post-trip. The Kruskal-Wallis test confirmed there were no group differences in any of these parameters (Chi-square = .1339286, df = 2, p= .935). The Friedman ANOVA (Chi-square (N=15, df=19) = 86.0033, p= .000001 indicated that there were significant pre-to-post-trip changes in some of these parameters. The Wilcoxon matched pairs test was used for post hoc assessments to confirm that the following 5 parameters had significantly deteriorated post-trip relative to pre-trip (difficulty concentrating p<0.018, slowed reactions p<0.037, level of fatigue p<0.008, work frustration p<0.05, and physical discomfort p<0.006). Again, the data show a pattern of accumulating fatigue across days at sea.

4   Discussion

This at-sea trial was undertaken to evaluate the impact of the submarine watch schedule variants on cognitive effectiveness of CF submariners. The goal of this trial was to compare these current results (which are based on actigraphically-measured sleep data) with the preliminary results in support of the HMCS Chicoutimi BOI (which were based on sleep behaviour assumptions).

The current results indicate a more severe impact on submariner performance than was evident in the earlier modeling effort in support of the HMCS Chicoutimi BOI. This is not surprising since sleep behaviour assumptions can only be scored as 100% sleep. Because the wrist actigraphs used in the current trial can discriminate a sleeping state from a waking state, they can also quantify the time it takes to get to sleep after retiring to bed (sleep latency) and measure any awake periods after sleep onset (wake after sleep onset (WASO)). This allows sleep latency and WASO to be subtracted from the total time in bed to generate the actual sleep minutes for each period in bed. This decreased amount of sleep (relative to the previous modeling efforts done in support of the Chicoutimi BOI) manifests itself as further decreases in submariner cognitive effectiveness.

Of the 3 non-watch-standers who participated in this trial, the FAST^{TM} models indicate that the CO's mean cognitive effectiveness dropped to levels equivalent to a blood alcohol of 0.05 on 4 separate days during the trial. The COXSN, like the CO, had consistent cognitive effectiveness levels below the ideal lowest level of 90%, but unlike the CO, the COXSN's mean cognitive effectiveness did not drop to a blood alcohol equivalent of 0.05%. The CERA's huge deficits in cognitive effectiveness are clearly due to very worrisome sleep hygiene issues.

The 1-in-2 back-watch-standers had unacceptably low cognitive effectiveness during their 1300 to 1900 hour watch, and potentially dangerously low cognitive effectiveness during their 0100 to 0700 hour watch. Similarly, the 1-in-2 front-watch-standers had low cognitive effectiveness during their 0700 to 1300 hour watch, and potentially dangerously low cognitive effectiveness during their 1900 to 0100 hour watch.

Since the 1-in-3-watch-standers worked different watches from day-to-day there is not sufficient systematic data to generate plots of cognitive effectiveness over days at sea, similar to the plots done for the 1-in-2-watch standers. Instead, the mean and minimum cognitive effectiveness for each of the 7 different 1-in-3-watch periods was plotted (Figure 3). This plot shows that mean cognitive effectiveness reached levels associated with impairment due to blood alcohol levels beyond 0.05% for each of the 1900 to 2300 hour and the 2300 to 0300 hour watches. However, the minimum cognitive effectiveness levels indicate performance impairment beyond 0.05% for the 0300 to 0700 hour watch and well beyond 0.08% for the 1900 to 2300 hour and 2300 to 0300 hour watches.

With respect to the subjective sleep rating data (which excluded the non-watch standers since there were only 2 subjects with usable data), there was not much difficulty getting to sleep since the various watch-standers were relatively sleep deprived. Nonetheless Figure 5 illustrates that difficulty getting to sleep was relatively constant over the first 4 days at sea, then difficulty getting to sleep fell over the next 6 days, and then rose again on Days 10 and 11, perhaps because of the anticipation of arriving home within a couple of days after a 3-month deployment. Depth of sleep was relatively deep and with no changes over days at sea.

There were no group differences in difficulty arising from sleep but generally difficulty arising from sleep increased over days at sea (Figure 8).

There were no group differences in subjective 'restedness' after sleep but the 'restedness' fell on the 2nd day at sea and remained significantly below Day 1 levels for the entire period at sea (Figure 10).

With respect to the VAS data, there were no group differences in alertness but relative to Day 1, alertness fell on Day 3 and remained low throughout the remaining days at sea (Figure 12). There were no changes in happiness over days at sea, but the 1-in-2-back-watch- standers and 1-in-2-front-watch-standers were less happy than the 1-in-3 engineers' watch (Figure 14). While there were no group differences in subjective levels of sleepiness or changes in sleepiness over days at sea, sleepiness was consistently elevated to mid-scale sleepiness levels throughout the trial.

With respect to the SOAP rating data, 5 of the 10 parameters (i.e., difficulty concentrating, slowed reactions, level of fatigue, work frustration, and physical discomfort) increased during the trial relative to the pre-trial baseline.

Of the previous 5 operational assessments conducted to evaluate cognitive effectiveness in CF operations [8-12], this at-sea submarine trial has produced the lowest levels of cognitive effectiveness. When one considers that this at-sea submarine trial was only a routine transatlantic transit as distinct from a high tempo work-up, or Command qualifying (Perisher) course, or a real interdiction operation, one is left to ponder how much worse cognitive effectiveness will become in a more demanding operational submarine scenario. There are alternative submarine watch schedules which would be far more sparing of crew cognitive effectiveness [7, 14]. As a result, in part, of a recommendation in the submarine watch-standing laboratory study [7], the U.S. Navy is investigating the idea of using straight-8-hour watch schedules in its submarines. Data have been collected aboard one attack submarine and one ballistic missile submarine and the Naval Submarine Medical Research Laboratory is presently preparing a technical report on this subject. However, given the current manning level of 48 submariners in our submarines, it is not yet clear that such a 1-in-3 watch system could be implemented. The question becomes "Can the CF operate its submarines with 16 submariners (48/3 = 16) on duty?"

In summary, while the CF submarine community is very professional and has consistently demonstrated excellent levels of operational effectiveness during Naval exercises with NATO allies, the submarine watch schedule variants currently in use cause unnecessary attrition of submariner performance and impacts on their quality of life. Operations at these degrees of fatigue invite slips (erroneous execution of correct intentions) and mistakes (formation of erroneous intentions).

5 Recommendations

If the CF is going to retain the current submarines and as these boats cycle into re-fit, refurbish them with fuel cells to provide air-independent-propulsion, there will be an opportunity to not only insert a module into the hull which will accommodate the fuel cell, but to at the same time insert a larger module which will also accommodate extra bunks to increase the size of the crew in order to facilitate a 1-in-3 watch system.

In such a watch system, the tactical submariners (currently 1-in-2 watches) would work 8 hours each day, leaving sufficient time for meals, personal administration and training, as well as an 8-hour time in bed. It is understood that the current 1-in-3 engineers' watch is restricted to 3 or 4-hour watches since 4 hours is the upper limit for watches in the very hot and very noisy environment of the engine room. It is also understood that not all the duty engineers are in the engine room spaces at the same time. Engineers also work in other technical spaces of the boat, and these spaces are not hot and noisy like the engine room. Therefore, if the engineers rotated between the engine room and the non-engine-room engineering spaces every 4 hours in concert with the same watch times as the 1-in-3 tactical watch keepers who are working 8-hour shifts, then a true 1-in-3 watch with 8-hour watches could be employed throughout all departments in the boats.

If the CF is going to acquire the newer Air-Independent-Propulsion diesel submarines such as the German 212 or 214 classes as presented in the Oct 10, 2007 Globe and Mail [2], it should be with the understanding that these new boats are highly automated and therefore have small crews. Such small crews would make it very difficulty to operate a 1-in-3 watch with 8-hour watches throughout the boat. Therefore, before proceeding with such a purchase, a task analysis should be carried out on these new boats to determine the crew size that would be pre-requisite to competent manning of the boat during any single watch. Once the manning requirements are known a contract should be negotiated with the manufacturer of these boats to increase the size of the boat in order to accommodate the requisite crew for a boat-wide 1-in-3 watch system based exclusively on 8-hour watches.

6   References

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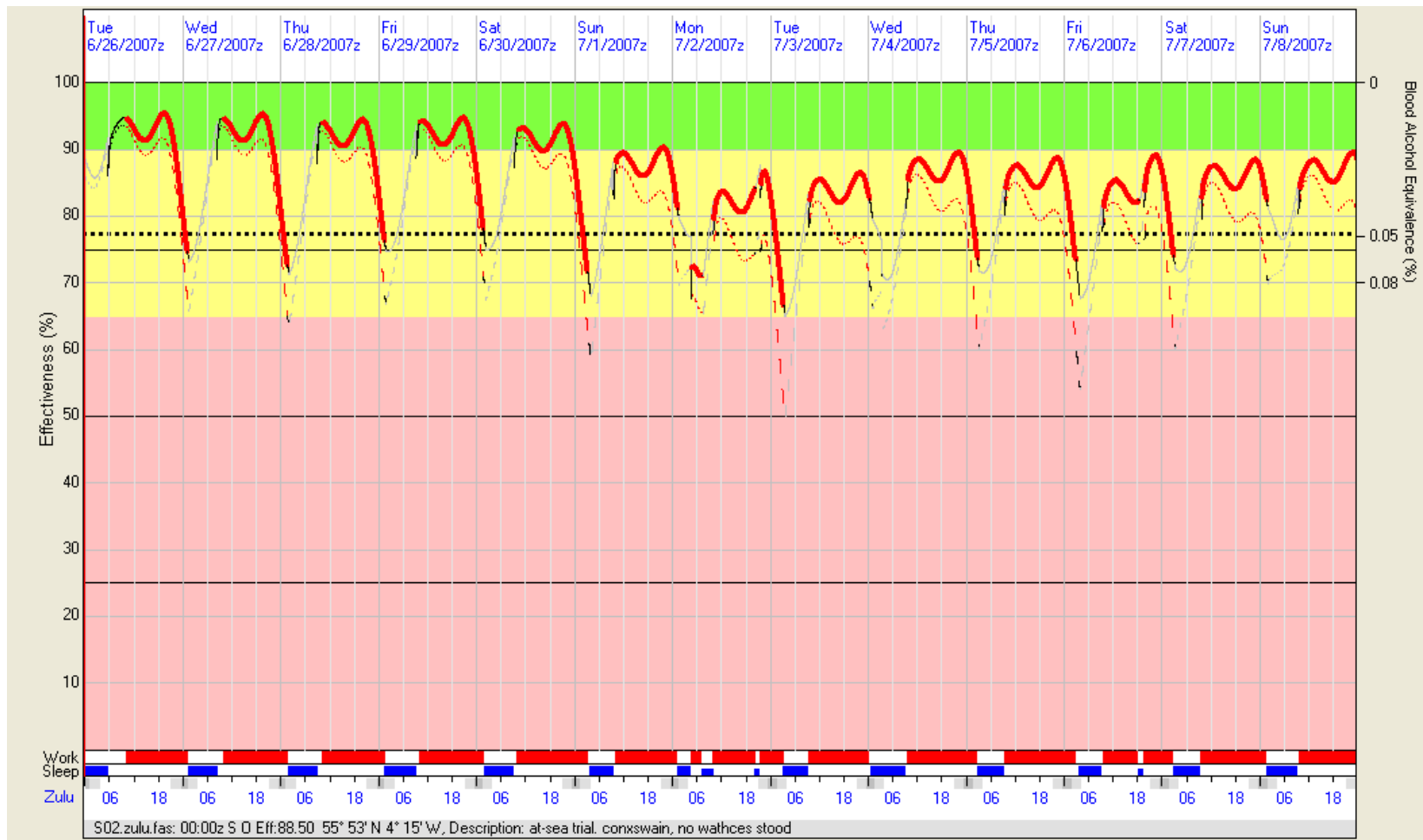
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Annex A   FAST^{TM} Models for Non-Watch-Standers

A.1   FAST^{TM} model for CO
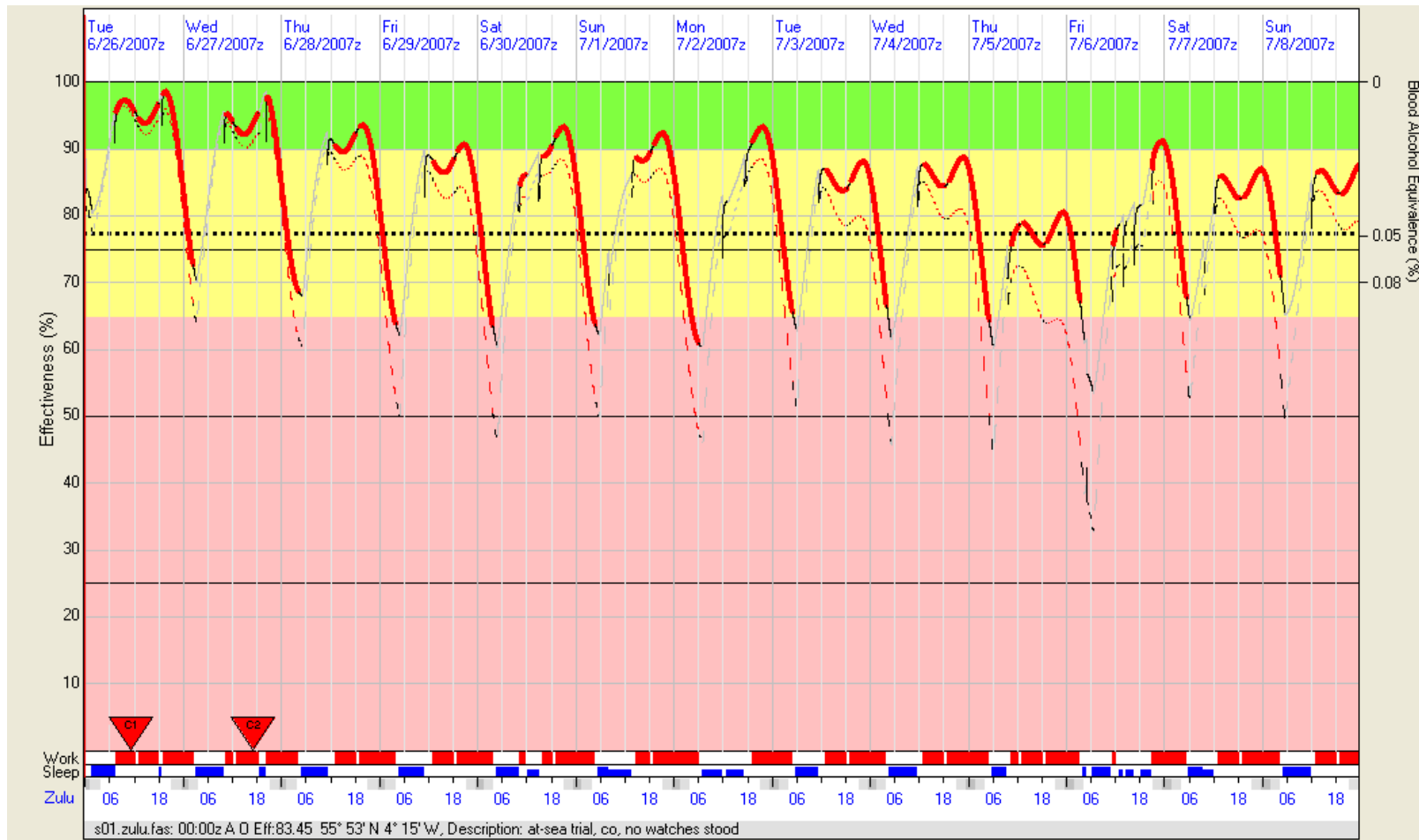
A.2   FAST™ model for Coxswain

A.3 FAST^{TM} model for CERA (Chief Engine Room Artificer)
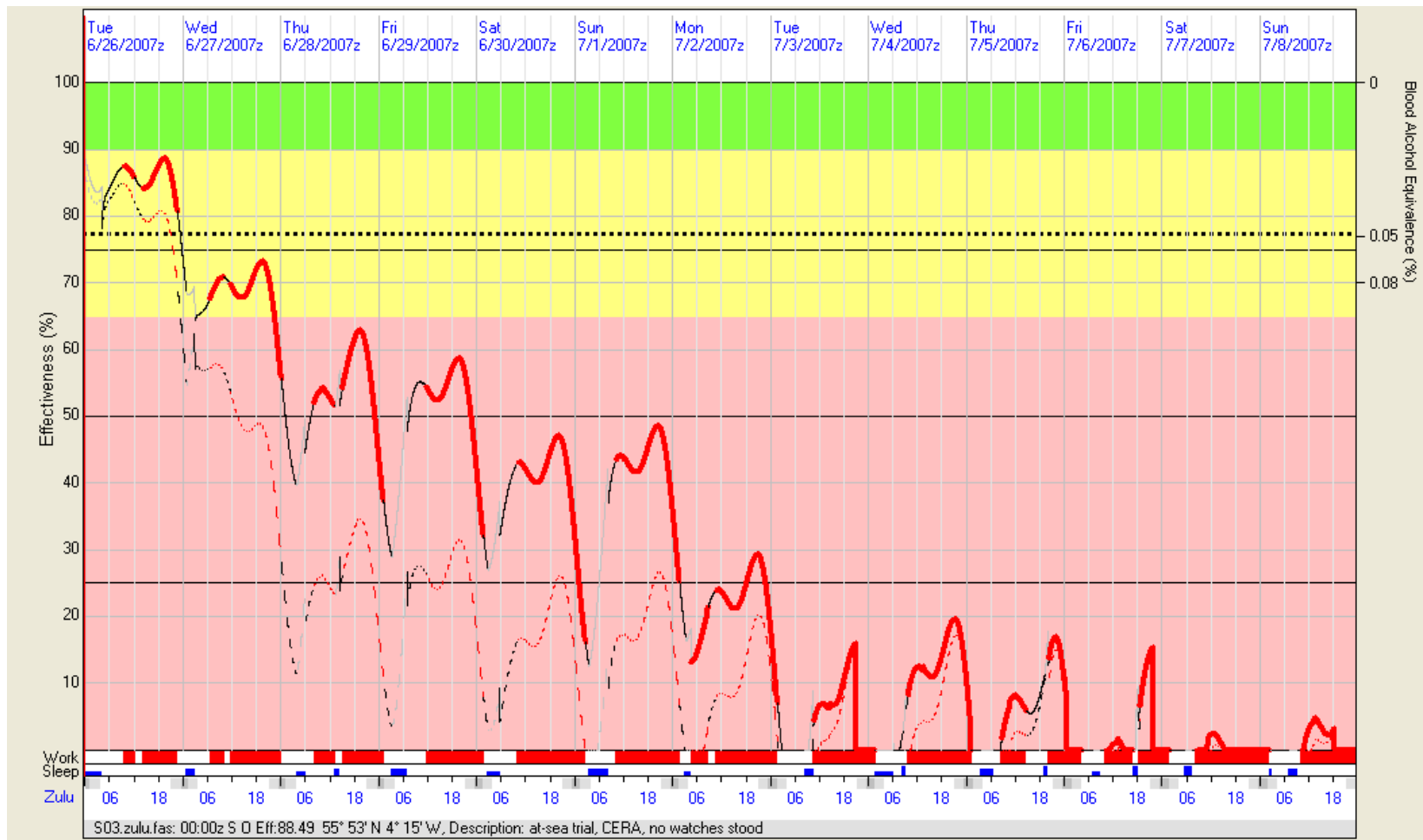
Annex B   FAST^{TM} Models for 1 in 2 Back-Watch-Standers

B.1   FAST^{TM} model for Subject 4 (watch leader)

B.2   B.2 FAST™ model for Subject 5

S05.zulu.fas: 00:00z S 0 Eff:88.50 55° 53' N 4° 15' W, Description: at-sea sub trial/1 in 2.back watch
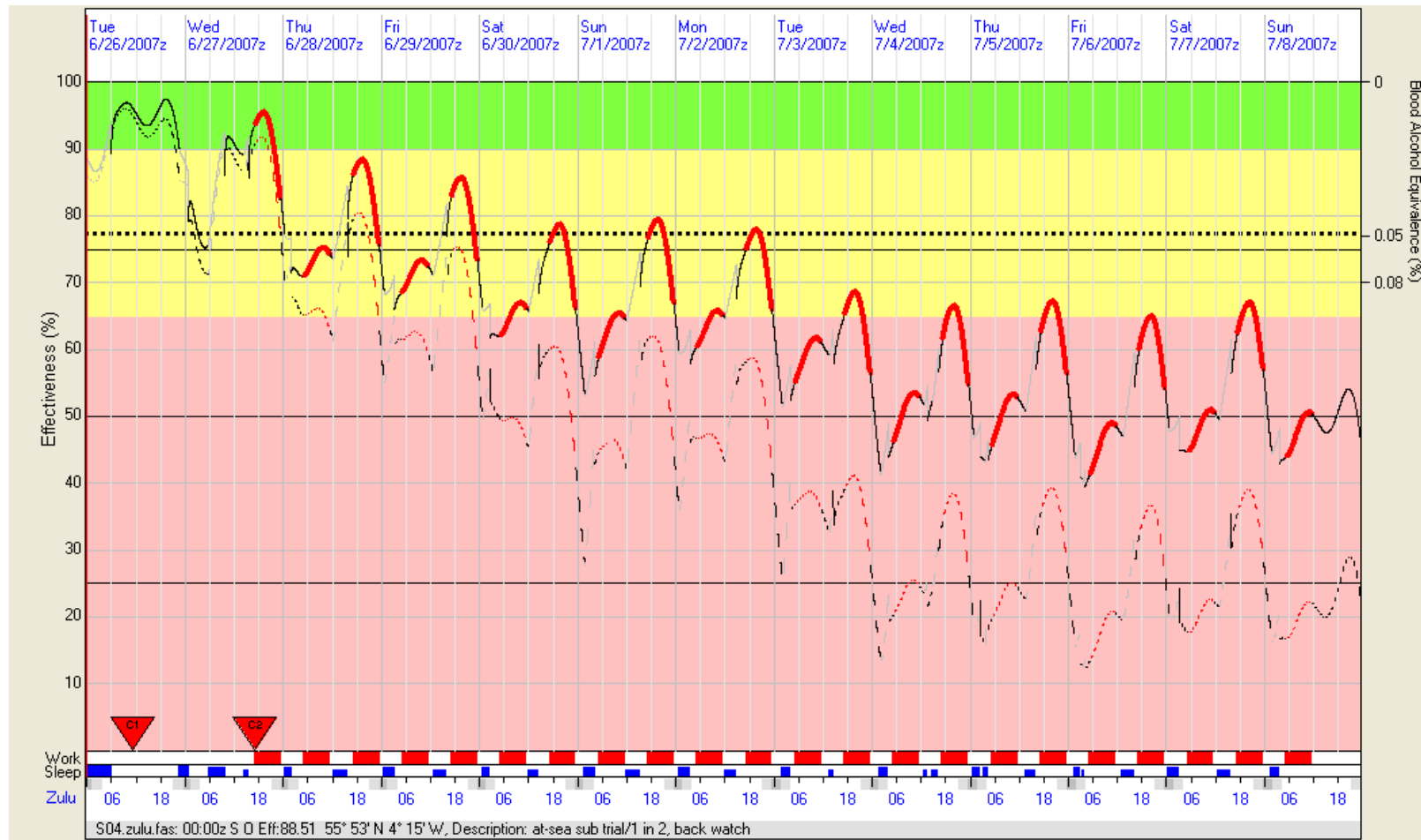
B.3   FAST^{TM} model for Subject 6
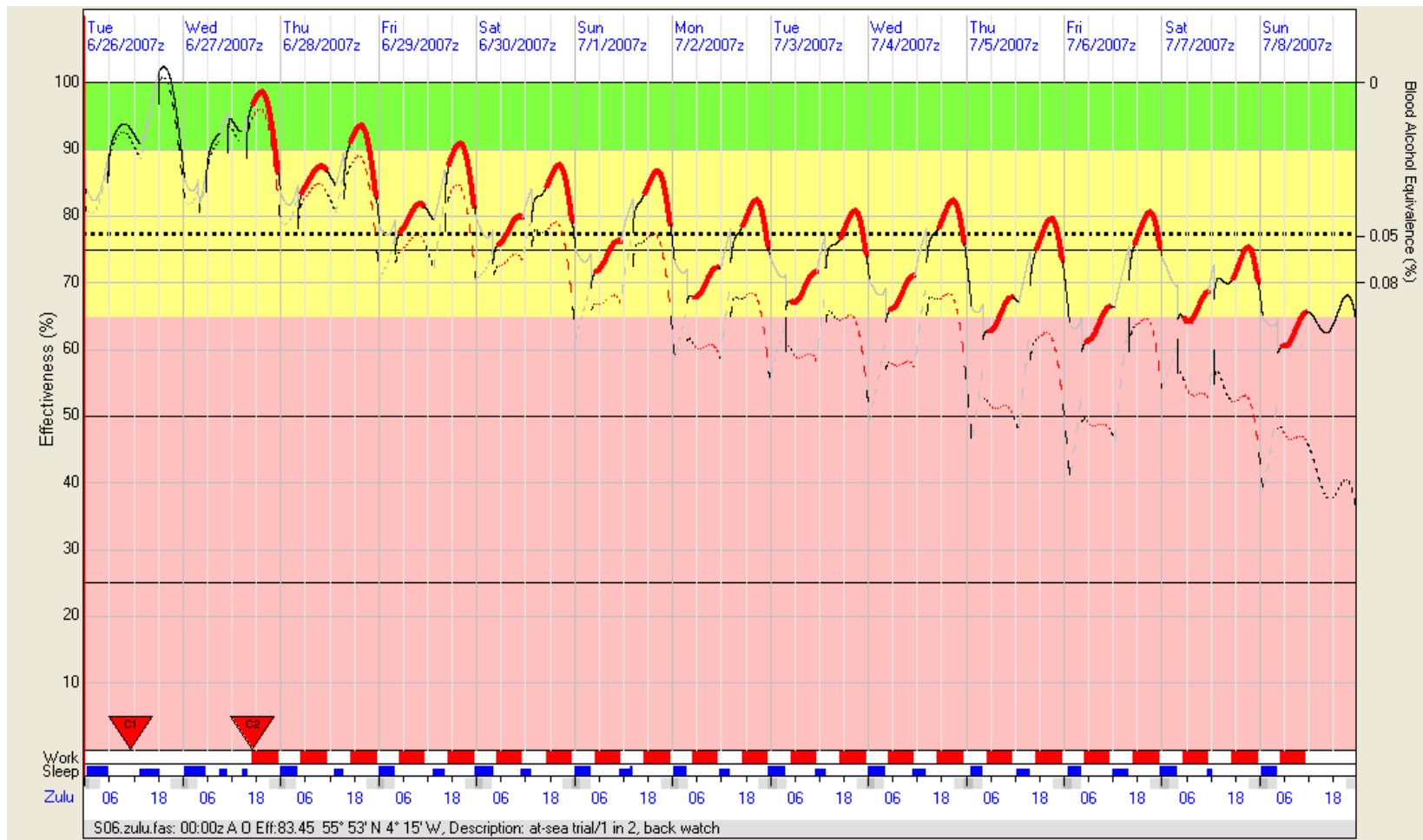
B.4   FAST^{TM} model for Subject 7

The wrist actigraph worn by subject 7 did not function. Thus there is no FAST^{TM} model for subject 7.

B.5 FAST™ model for Subject 8
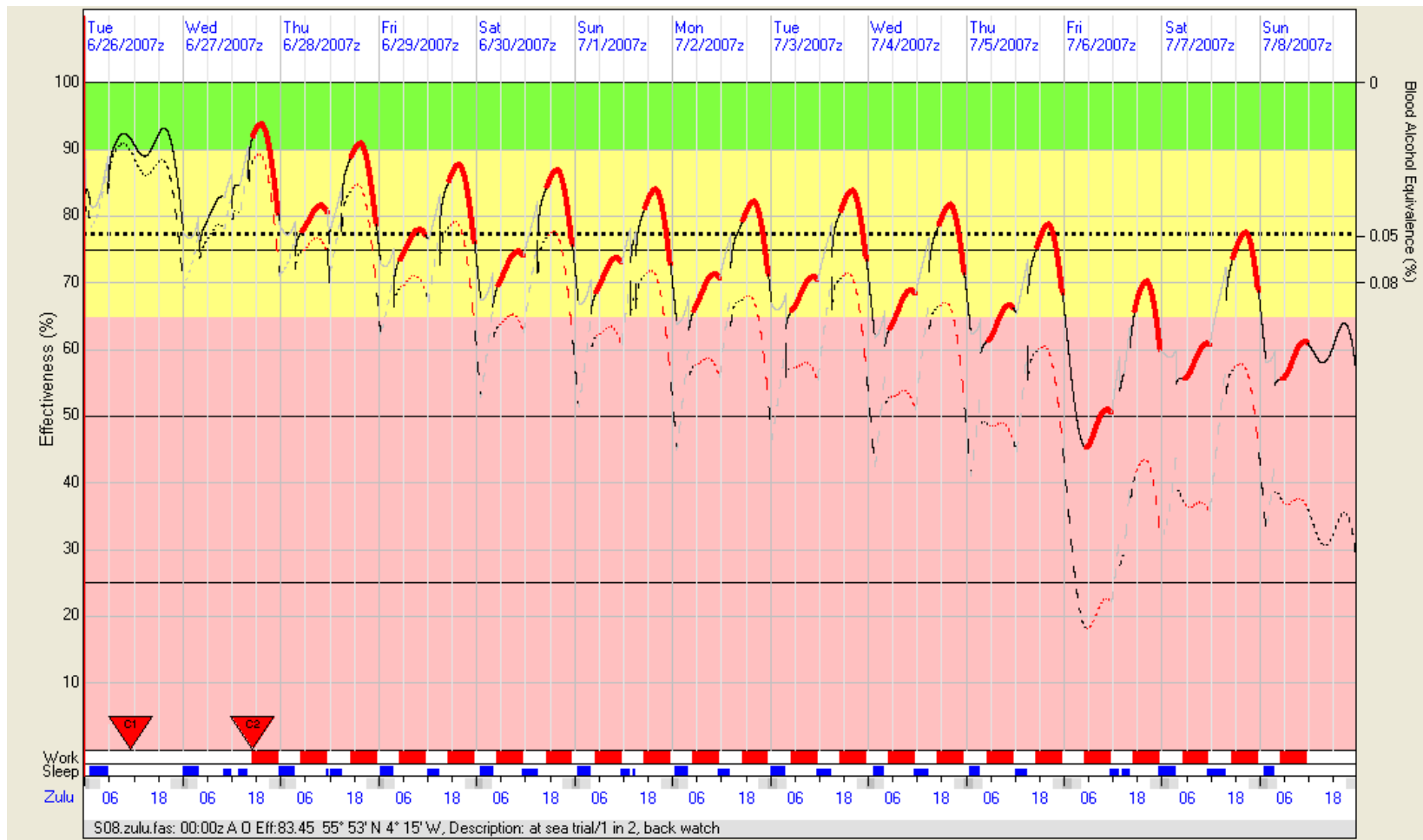
B.6 FAST^{TM} model for Subject 9
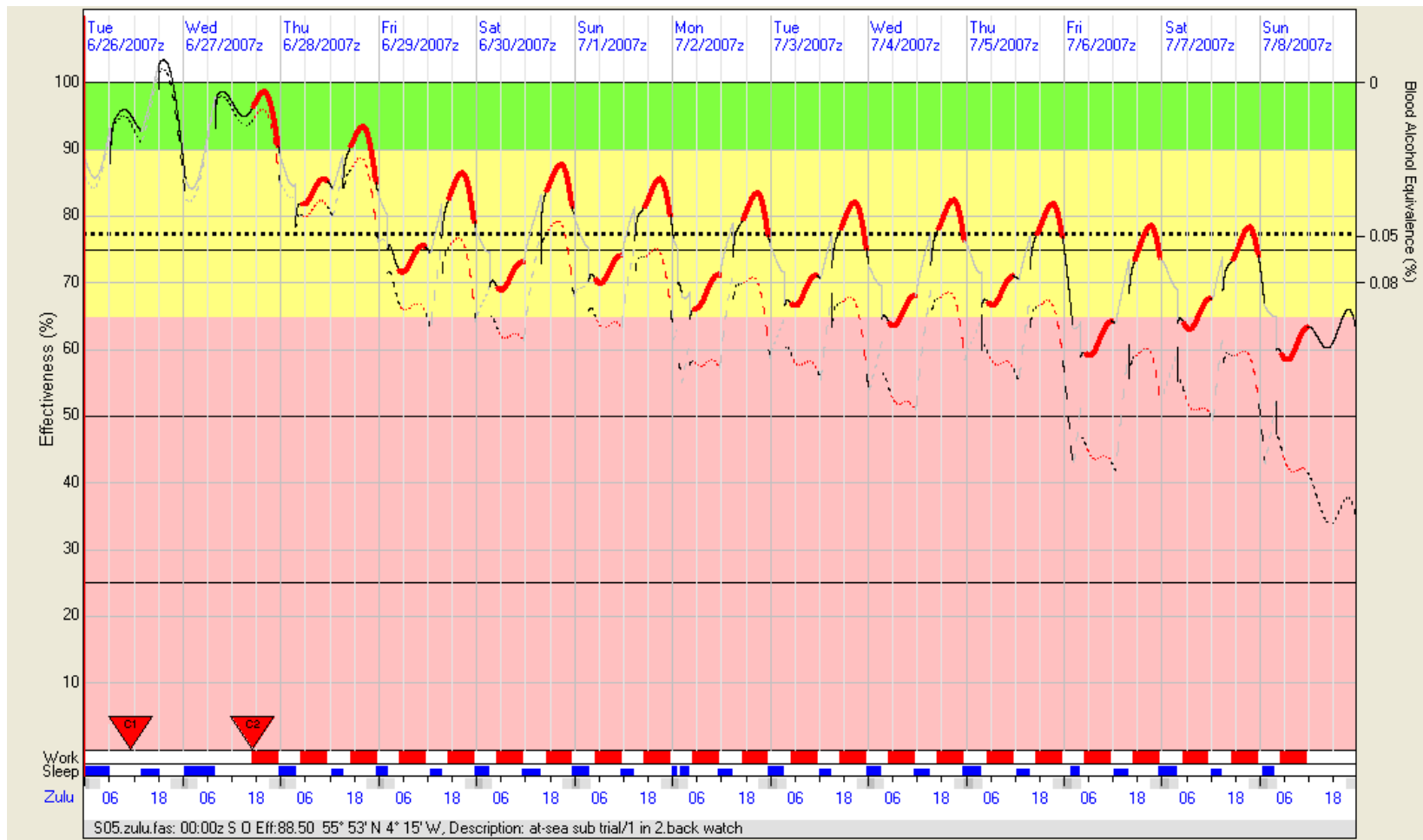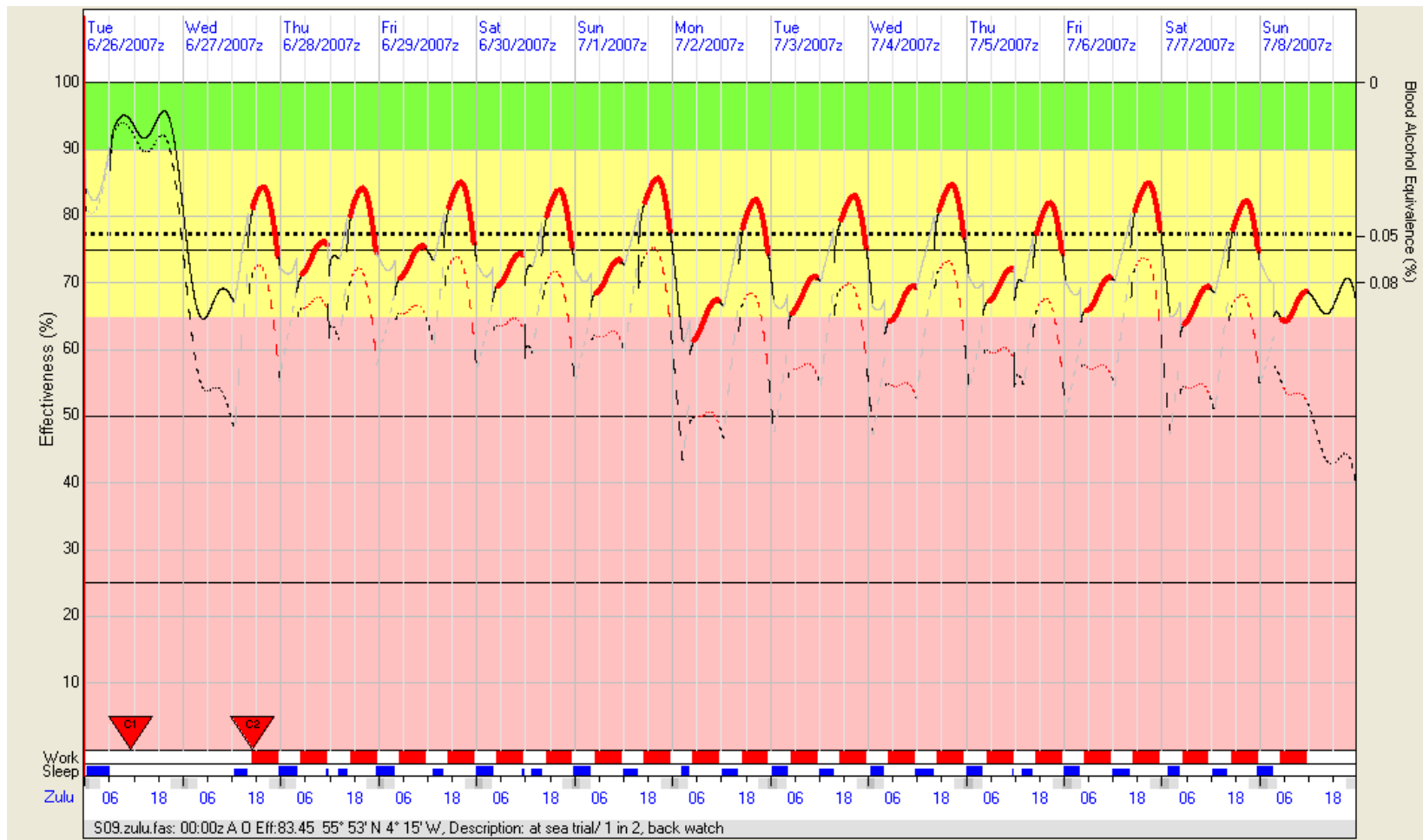
Annex C   FAST^{TM} Models for 1 in 2 Front-Watch-Standers

C.1   FAST^{TM} model for subject 10 (watch leader)
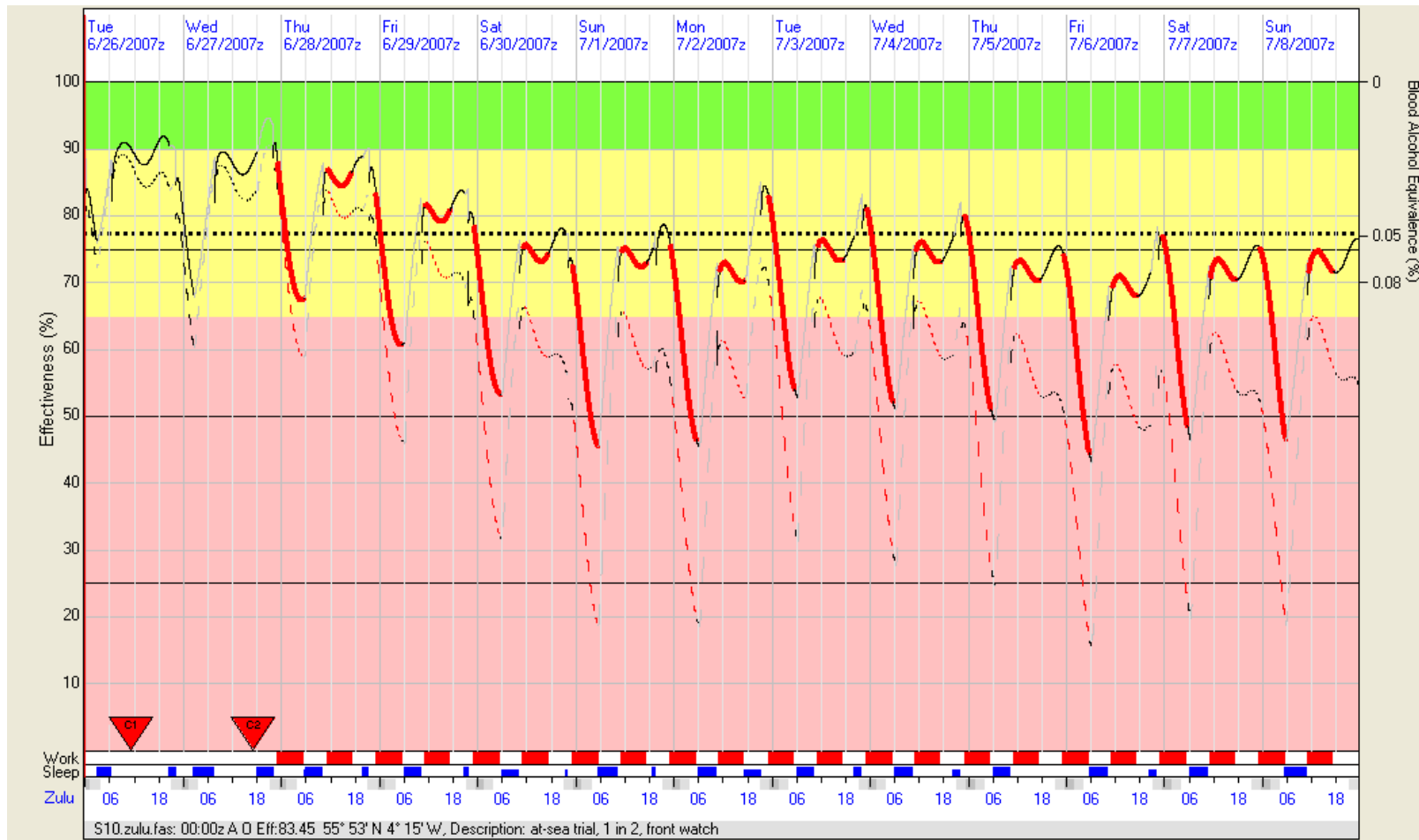
C.2   FAST^{TM} model for subject 11

C.3 FAST™ model for subject 12

S12.zulu.fas: 00:00z S 0 Eff:88.50 55° 53' N 4° 15' W, Description: at sea trial/ 1 in 2, front watch
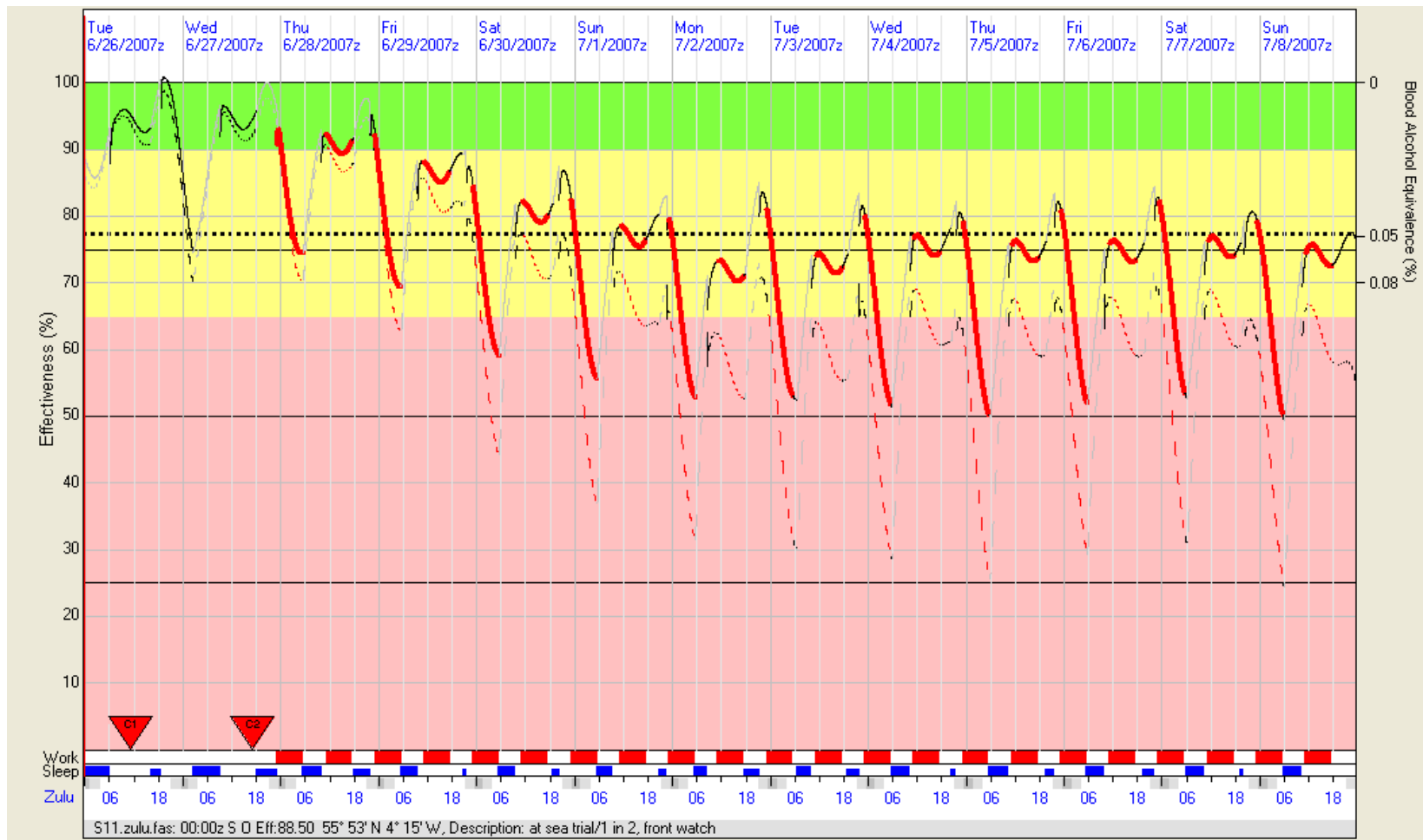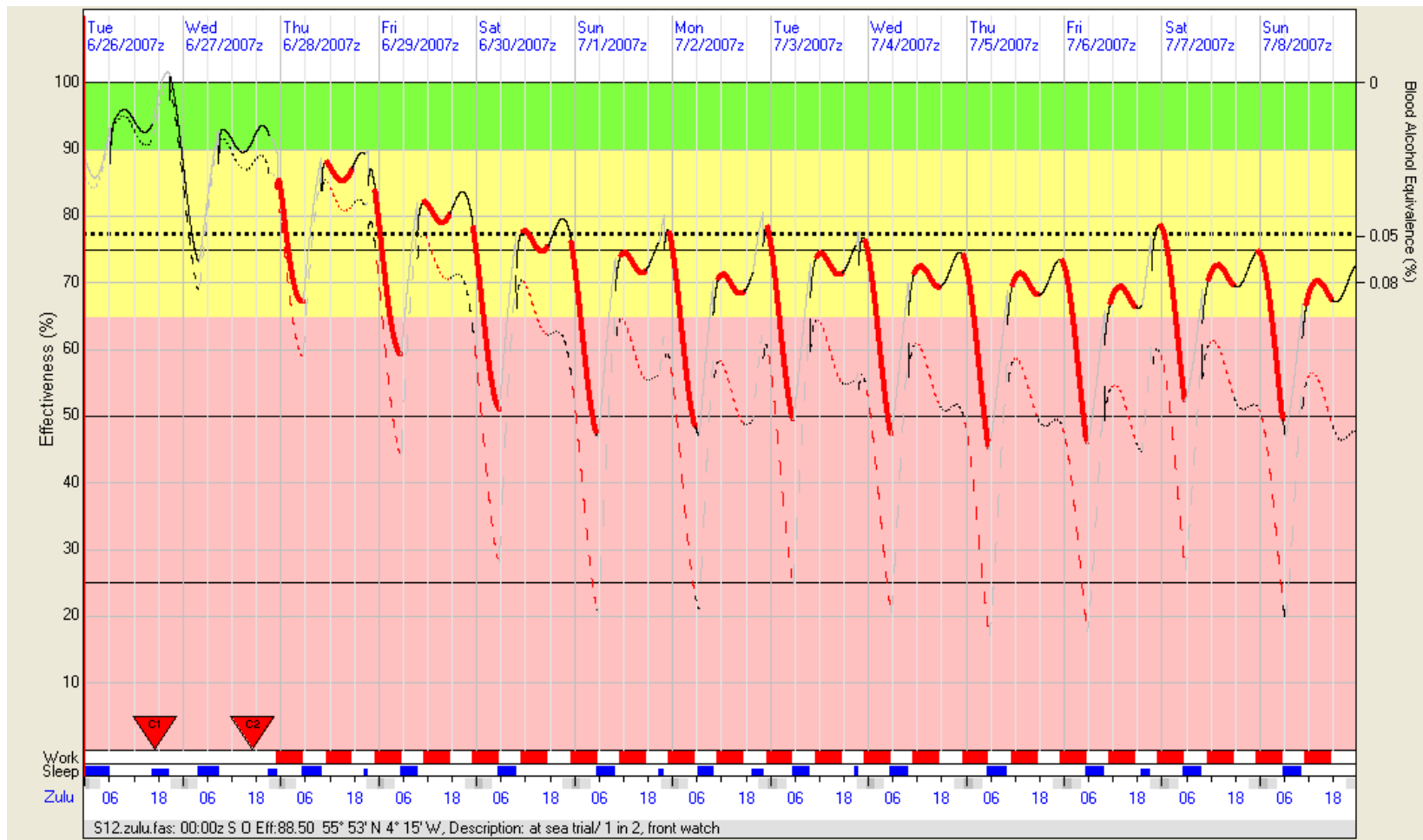
C.4 FAST^{TM} model for subject 13
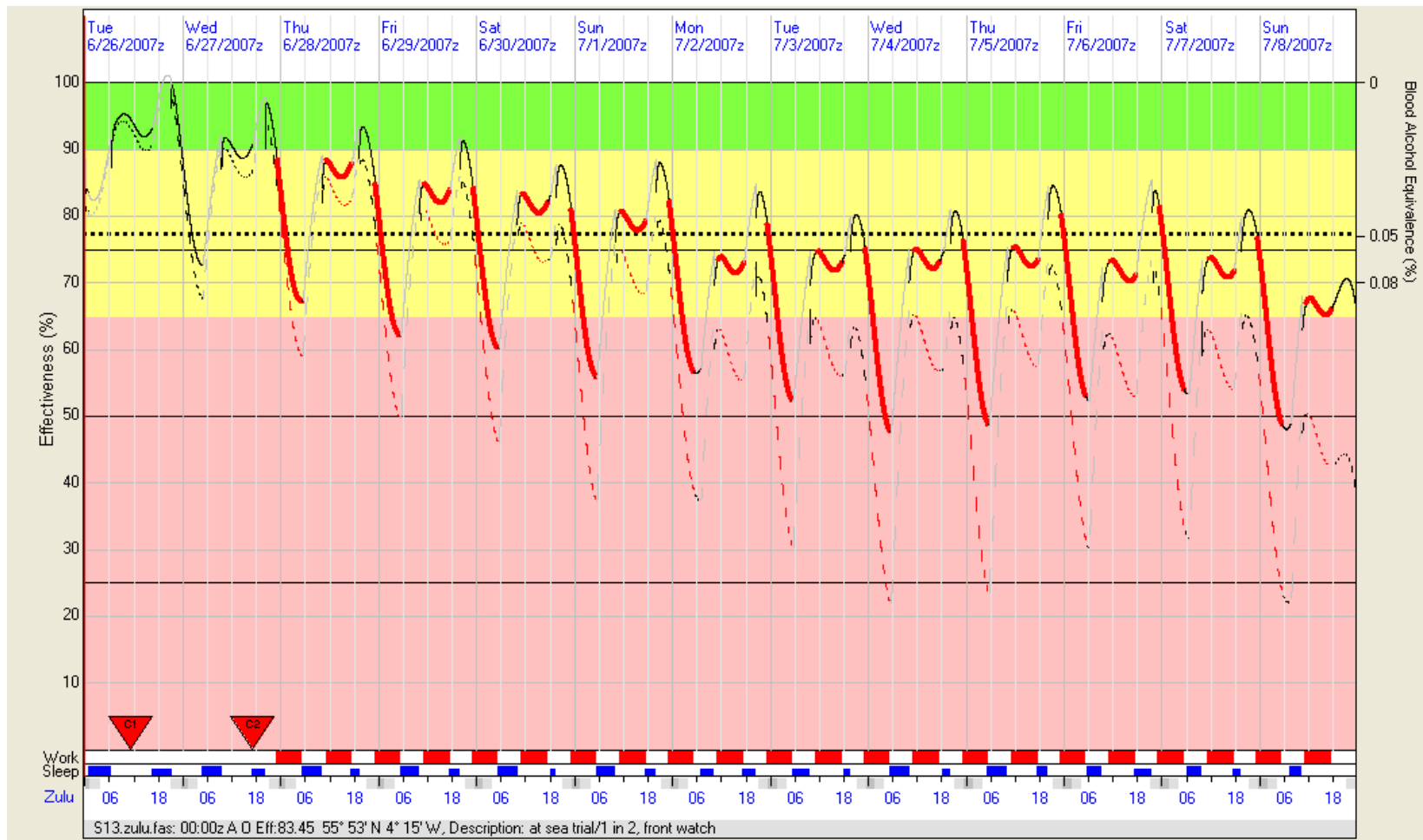
C.5 FAST^{TM} model for subject 14

C.6 FAST^{TM} model for subject 15

S15.zulu.fas: 00:00z A 0 Eff:83.45 55° 53' N 4° 15' W, Description: at sea trial/ 1 in 2, front watch
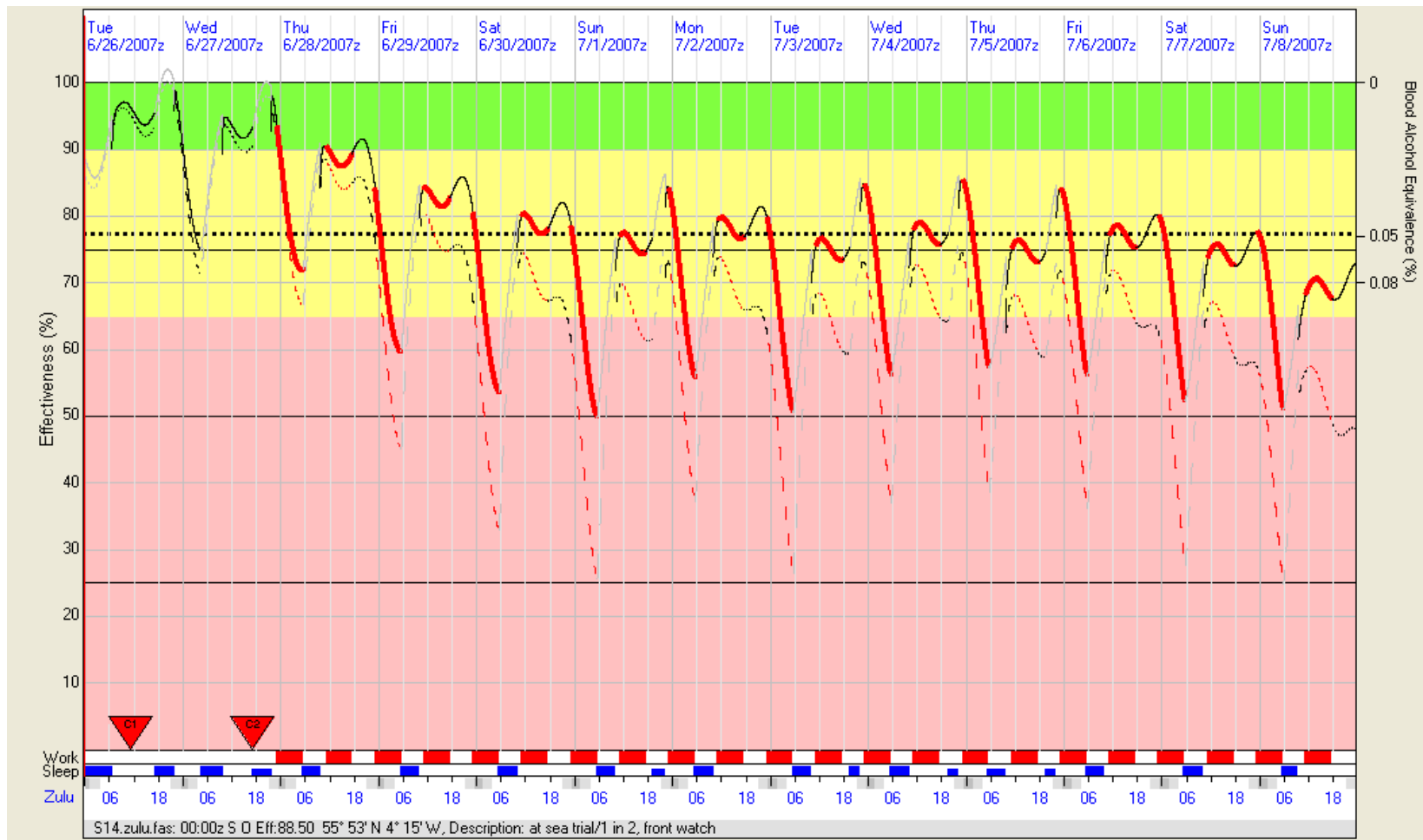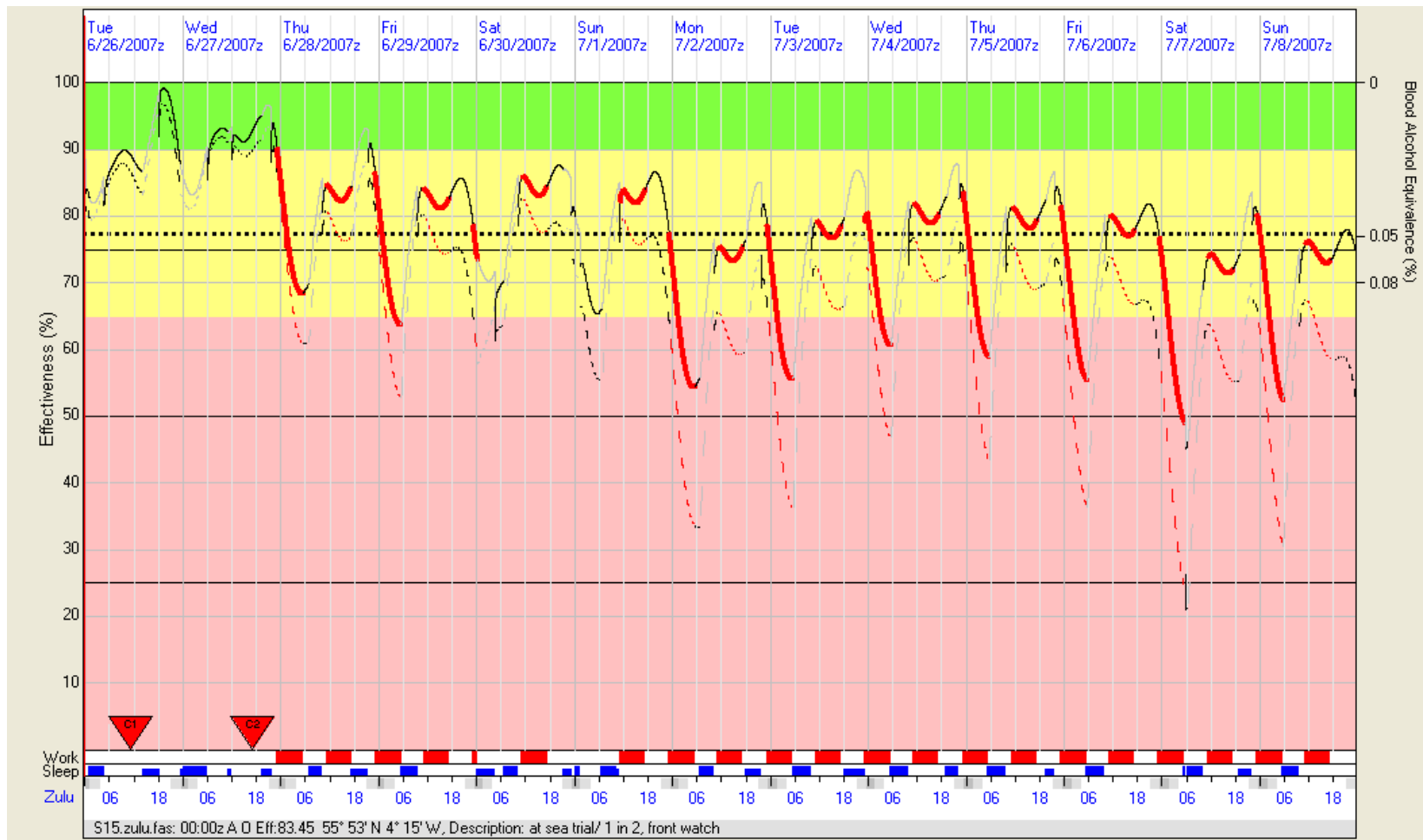
Annex D   FAST^{TM} Models for 1 in 3 Engineers' Watch

D.1   FAST^{TM} model for subject 16
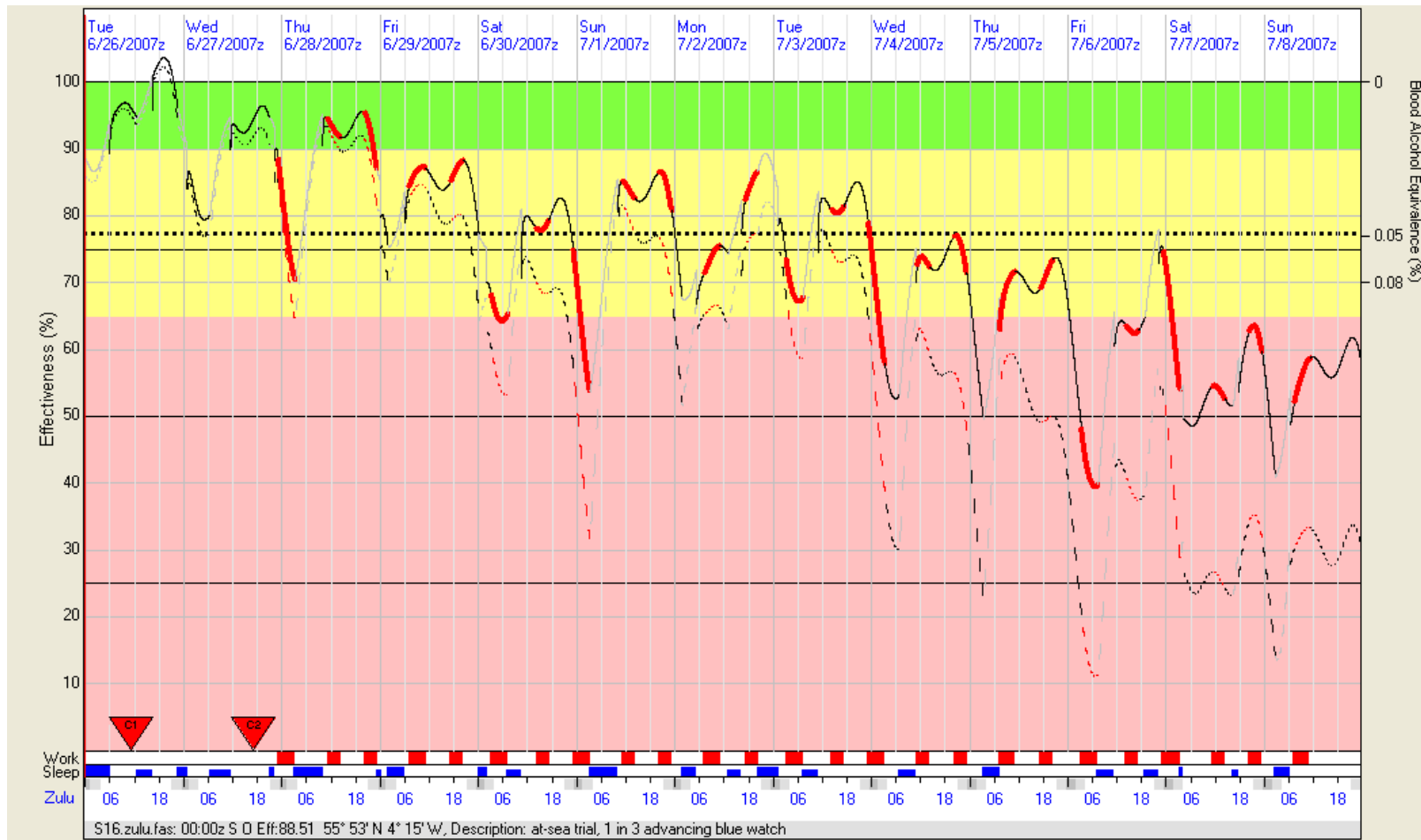
D.2   FAST^{TM} model for subject 17
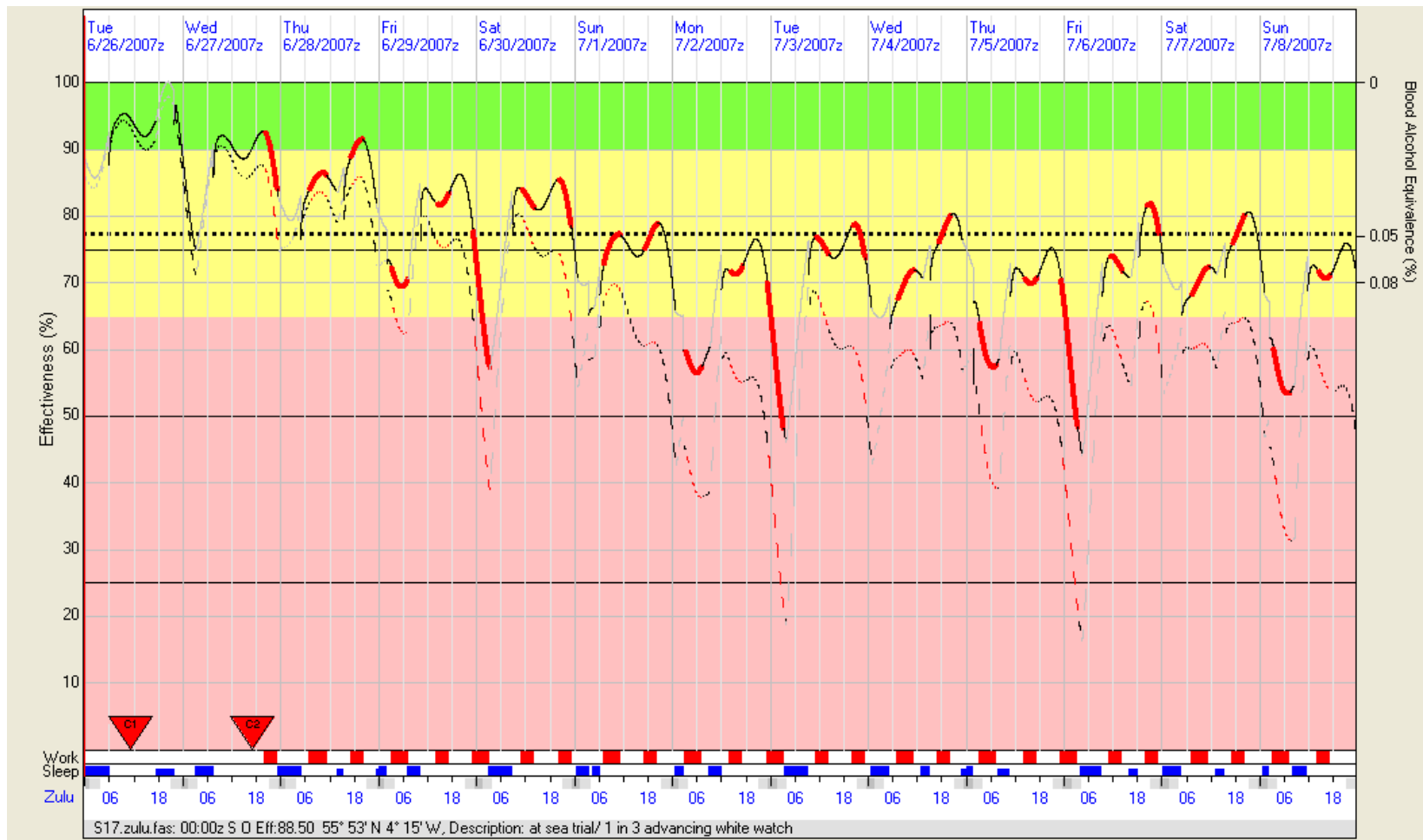
S17.zulu.fas: 00:00z S O Eff:88.50 55° 53' N 4° 15' W, Description: at sea trial/ 1 in 3 advancing white watch

D.3 FAST^{TM} model for subject 18

S18.zulu.fas: 00:00z S O Eff:88.50 55° 53' N 4° 15' W, Description: at-sea trail/1 in 3 advancing blue to white watch

D.4 FAST^{TM} model for subject 19

S19.zulu.fas: 00:00z A 0 Eff:83.45 55° 53' N 4° 15' W, Description: at-sea trial/1 in 3 advancing red watch

D.5 FAST^{TM} model for subject 20

S20.zulu.fas: 00:00z A 0 Eff:83.45 55° 53' N 4° 15' W, Description: at-seat trial/1 in 3 advancing red watch
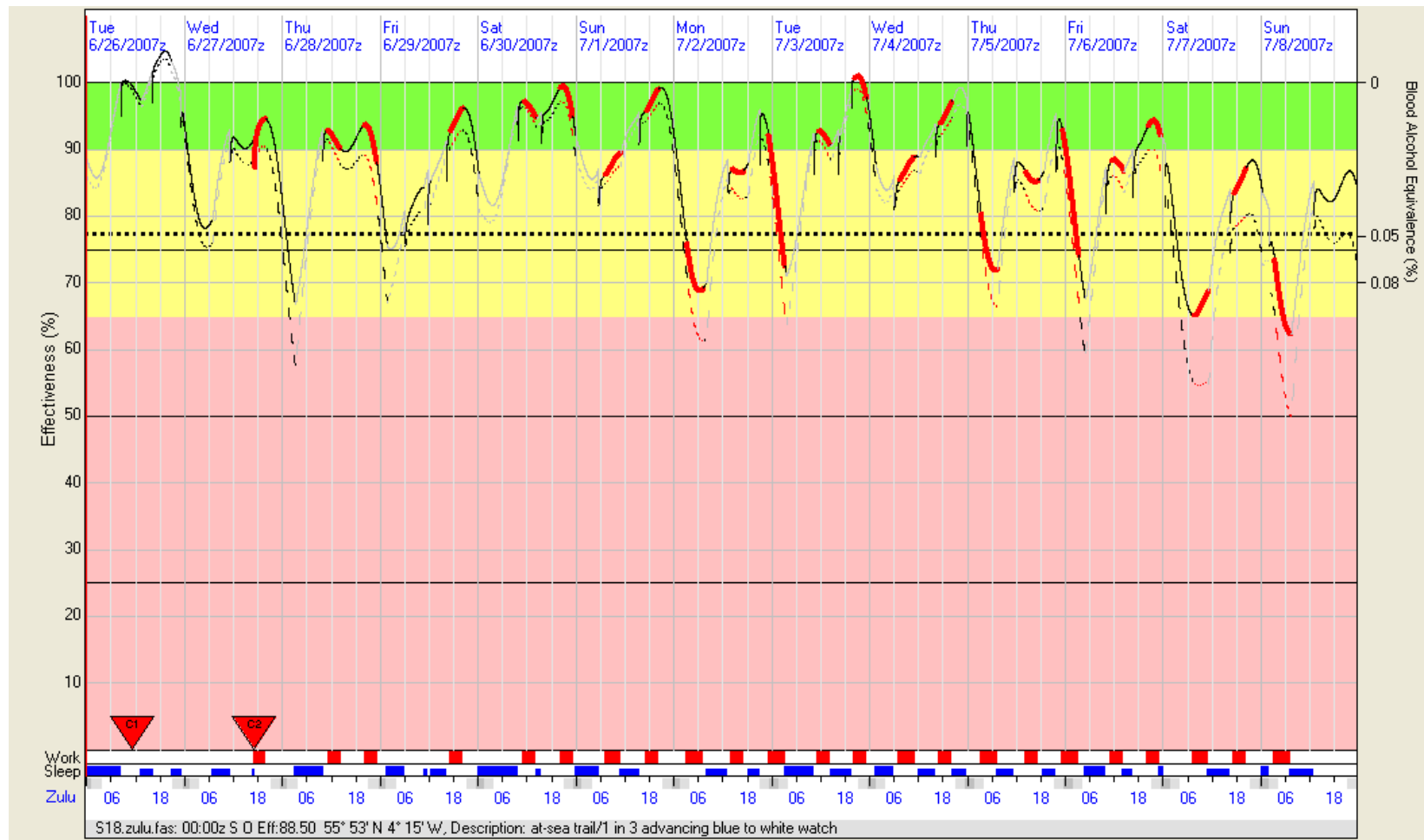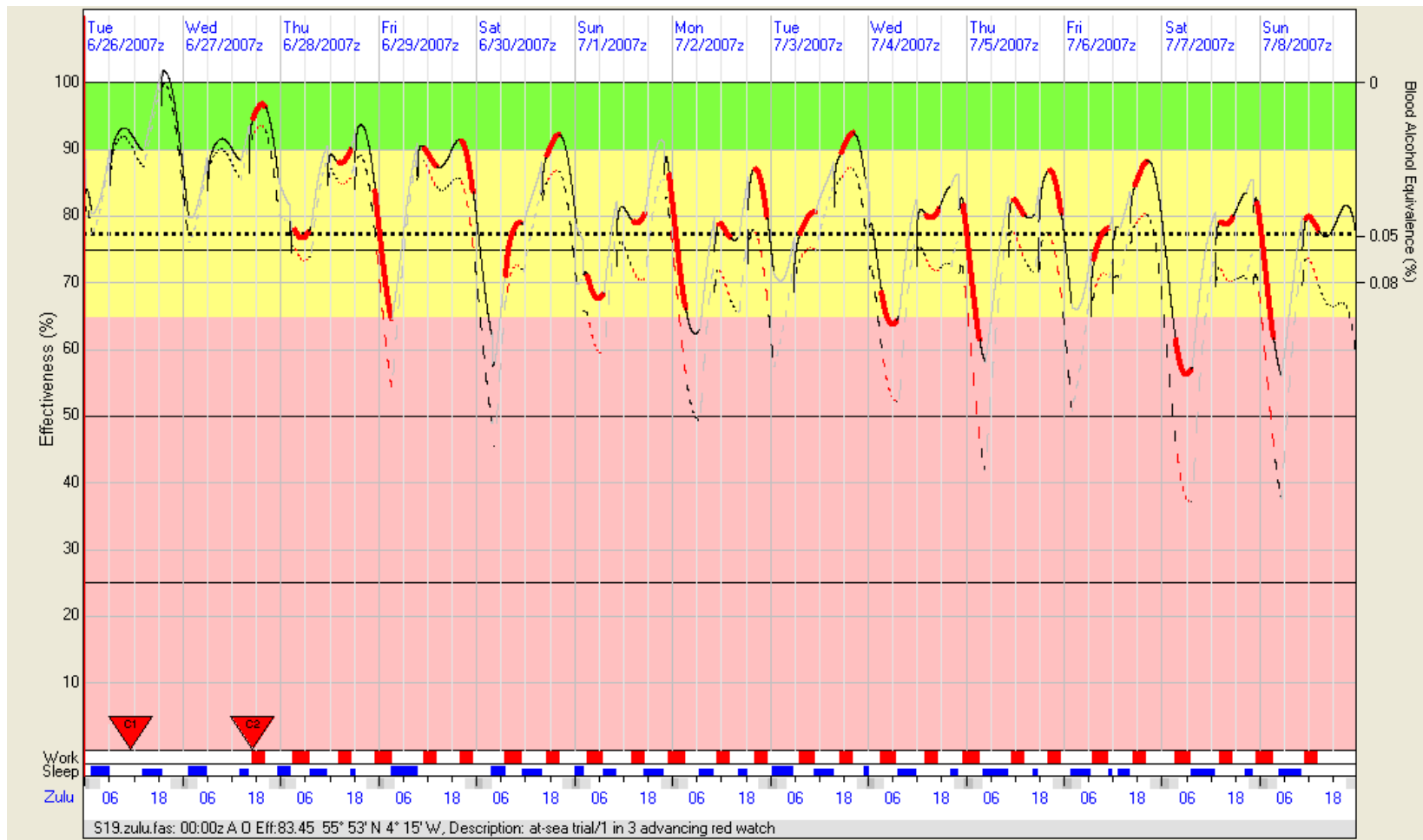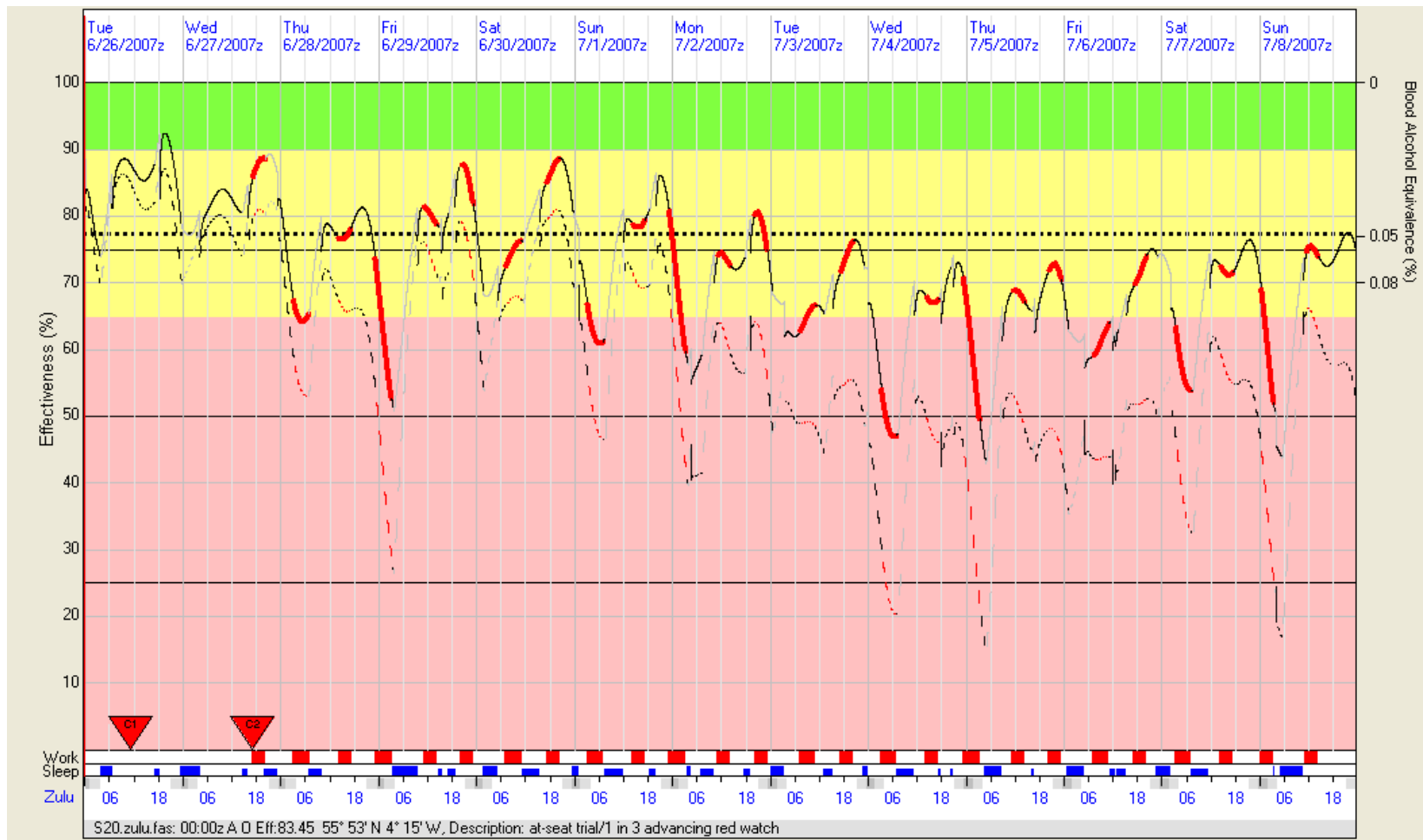
D.6   FAST^{TM} model for subject 21
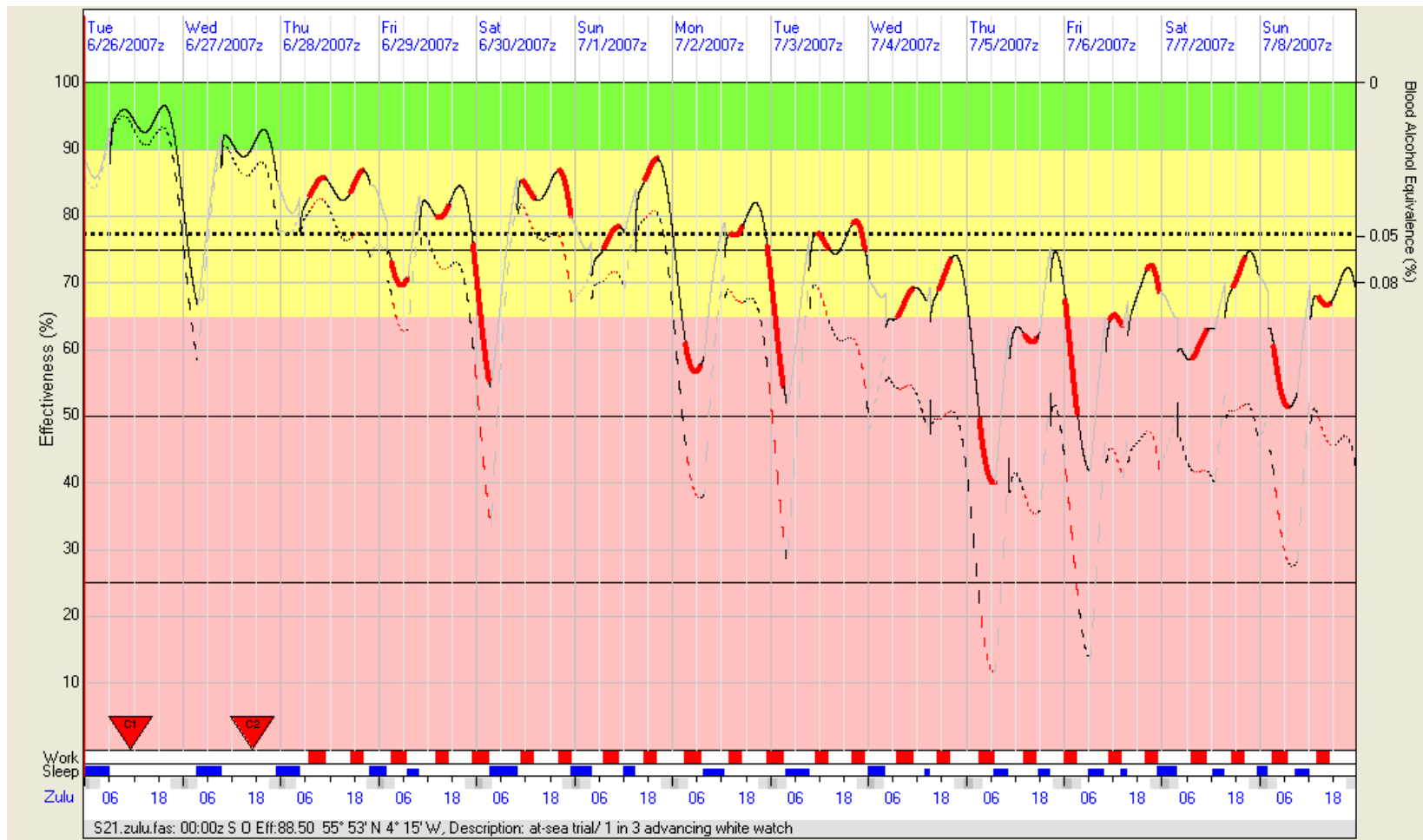
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Annex E   Sleep, Activity, Fatigue and Task Effectiveness (SAFTE) Model

E.1   Fatigue Avoidance Scheduling Tool (*FAST*^{TM})

The Sleep, Activity, Fatigue and Task Effectiveness (SAFTE) model integrates quantitative information about (1) circadian rhythms in metabolic rate, (2) cognitive performance recovery rates associated with sleep, and cognitive performance decay rates associated with wakefulness, and (3) cognitive performance effects associated with sleep inertia to produce a 3-process model of human cognitive effectiveness.

The SAFTE model has been under development by Dr. Steven Hursh for more than a decade. Dr. Hursh, formerly a research scientist with the US Army, is employed by SAIC (Science Applications International Corporation) and Johns Hopkins University and is currently under contract to the WFC (Warfighter Fatigue Countermeasures) R&D Group and NTI, Inc. to modify and expand the model.

The general architecture of the SAFTE model is shown in Figure 1. A circadian process influences both cognitive effectiveness and sleep regulation. Sleep regulation is dependent upon hours of sleep, hours of wakefulness, current sleep debt, the circadian process and sleep fragmentation (awakenings during a sleep period). Cognitive effectiveness is dependent upon the current balance of the sleep regulation process, the circadian process, and sleep inertia.

Schematic of SAFTE Model
Sleep, Activity, Fatigue and Task Effectiveness Model
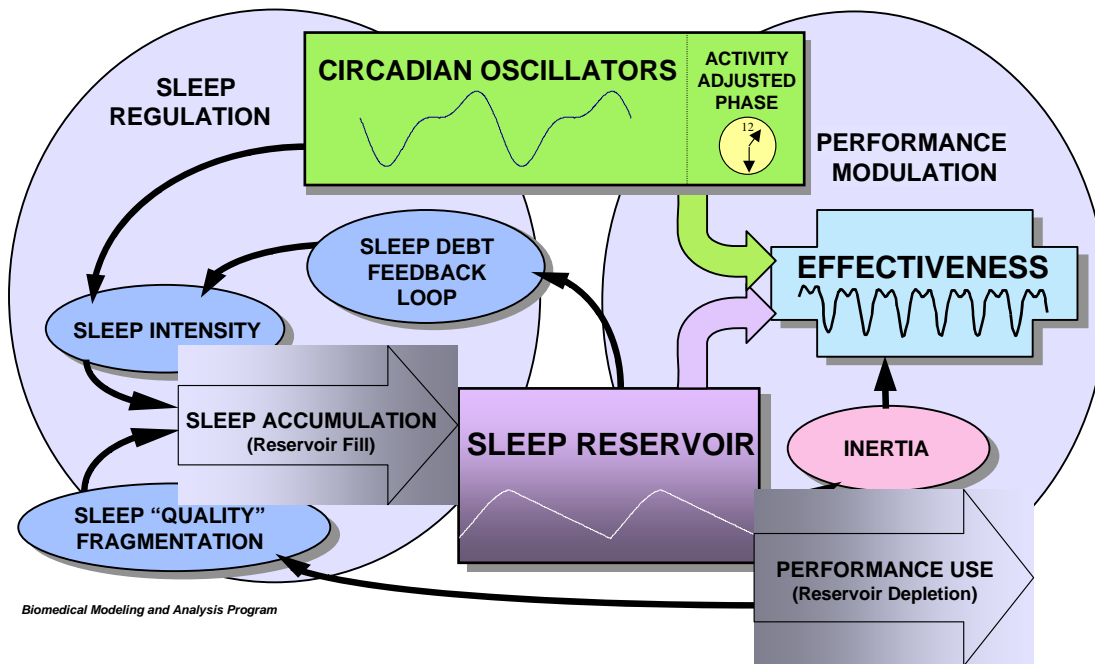
Figure 1. Schematic of SAFTE Model

SAFTE has been validated against group mean data from a Canadian laboratory that were not used in the model's development (Hursh et al., in review). Additional laboratory and field validation studies are underway and the model has begun the USAF Verification, Validation and Accreditation (VV&A) process.

The model does not incorporate the effects of pharmacological alertness aids; chronic fatigue (motivational exhaustion); chronic fatigue syndrome; fatiguing physiological factors such as exercise, hypoxia or acceleration; sleep disorders; or the fatiguing effects of infection.

The SAFTE Model has a number of essential features that distinguish it from other attempts to model sleep and fatigue (Table D-1). Together, these features of the model allow it to make very accurate predictions of performance under a variety of work schedules and levels of sleep deprivation.

Table D-1. SAFTE model essential features.

KEY FEATURES	ADVANTAGES
Model is homeostatic. Gradual decreases in sleep debt decrease sleep intensity. Progressive increases in sleep debt produced by extended periods of less than optimal levels of sleep lead to increased sleep intensity.	Predicts the normal decline in sleep intensity during the sleep period. Predicts the normal equilibrium of performance under less than optimal schedules of sleep.
Model delays sleep accumulation at the start of each sleep period.	Predicts the detrimental effects of sleep fragmentation and multiple interruptions in sleep.
Model incorporates a multi-oscillator circadian process.	Predicts the asymmetrical cycle of performance around the clock.
Circadian process and Sleep-Wake Cycle are additive to predict variations in performance.	Predicts the mid-afternoon dip in performance, as well as the more predominant nadir in performance that occurs in the early morning.
Model modulates the intensity of sleep according to the time of day.	Predicts circadian variations in sleep quality. Predicts limits on performance under schedules that arrange daytime sleep.
Model includes a factor to account for the initial lag in performance upon awakening.	Predicts sleep inertia that is proportional to sleep debt.
Model incorporates adjustment to new time zones or shift schedules	Predicts temporary "jet-lag" effects and adjustment to shift work

The Fatigue Avoidance Scheduling Tool (*FAST*™) is based upon the SAFTE model. *FAST*™, developed by NTI, Inc. as an AF SBIR (Air Force, Small Business Innovative Research) product, is a Windows® program that allows planners and schedulers to estimate the average effects of various schedules on human performance. It allows work and sleep data entry in graphic and text formats. A work schedule comprised of three 36-hr missions each separated by 12 hours is shown as red bands on the time line across the bottom of the graphic presentation format in Figure 2. Average performance effectiveness for work periods may be extracted and printed as shown in the table below the figure.
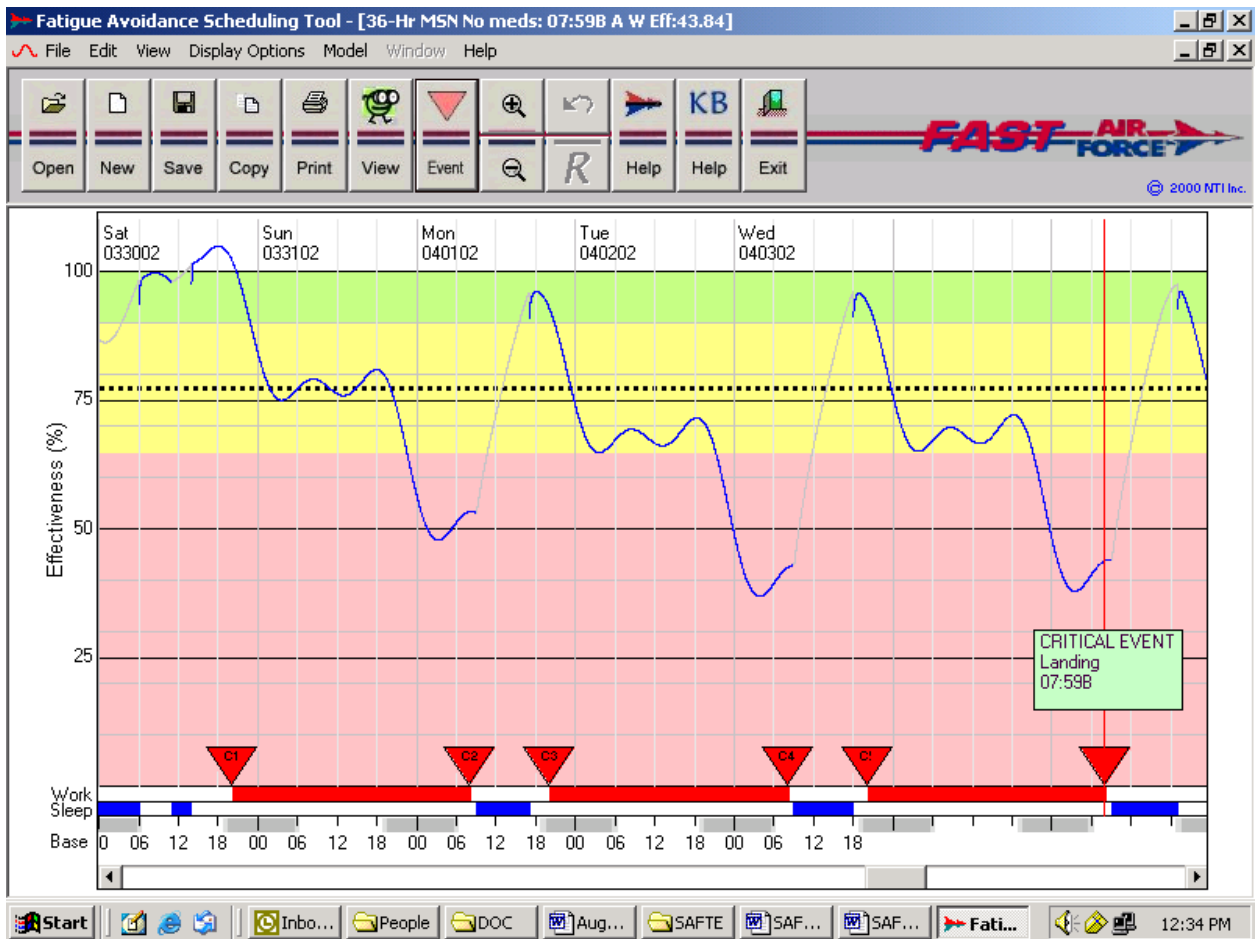
AWAKE			WORK		
Start Day - Hr	Duration (Minutes)	Mean Effectiveness	Start Day - Hr	Duration (Minutes)	Mean Effectiveness
0 - 06:00	300	98.97	0 - 20:00	1079	81.14
0 - 14:00	2580	76.42	1 - 14:00	1080	63.97
2 - 17:00	2400	64.78	2 - 20:00	1079	71.23
4 - 18:00	2340	64.58	3 - 14:00	1080	54.51
6 - 19:00	1741	72.23	4 - 20:00	1079	72.00
			5 - 14:00	1080	54.92

Figure 2: Sample FAST^{tm} display. The triangles represent waypoint changes that control the amount of light available at awakening and during various phases of the circadian rhythm. The table shows the mission split into two work intervals, first half and second half.

Sleep periods are shown as blue bands across the time line, below the red bands.

The vertical axis of the diagram represents composite human performance on a number of associated cognitive tasks. The axis is scaled from zero to 100%. The oscillating line in the diagram represents expected group average performance on these tasks as determined by time of day, biological rhythms, time spent awake, and amount of sleep. We would expect the predicted performance of half of the people in a group to fall below this line.

The green area on the chart ends at the time for normal sleep, ~90% effectiveness.

The yellow indicates caution.

The area from the dotted line to the red area represents performance level during the nadir and during a 2nd day without sleep.

The red area represents performance effectiveness after 2 days and a night of sleep deprivation.

The expected level of performance effectiveness is based upon the detailed analysis of data from participants engaged in the performance of cognitive tasks during several sleep deprivation studies conducted by the Army, Air Force and Canadian researchers. The algorithm that creates the predictions has been under development for two decades and represents the most advanced information available at this time.

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[3]   Hursh SR (1998). *Modeling Sleep and Performance within the Integrated Unit Simulation System (IUSS)*. Technical Report Natick/TR-98/026L. Science and Technology Directorate, Natick Research, Development and Engineering Center, United States Army Soldier Systems Command, Natick, Massachusetts 01760-5020.

[4]   Hursh SR, Redmond DP, Johnson ML, Thorne DR, Belenky G, Balkin TJ, Miller JC, Eddy DR, Storm WF (2003). The DOD Sleep, Activity, Fatigue and Task Effectiveness Model. *Proceedings of the 12th Conference on Behavior Representation in Modeling and Simulation (BRIMS 2003)*, 03-BRIMS-001, 14-15 May 2003, Mesa, Arizona.

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List of symbols/abbreviations/acronyms/initialisms

ANOVA	Analysis of Variance
BAC	Blood Alcohol Level
BOI	Board of Inquiry
CERA	Chief Engine Room Artificer
CF	Canadian Forces
CO	Commanding Officer
COXSN	Coxswain
DND	Department of National Defence
DRDC	Defence Research & Development Canada
DRDKIM	Director Research and Development Knowledge and Information Management
FAST^{TM}	Fatigue Avoidance Scheduling Tool
LSD	Least Significant Difference
PVT	Psychomotor Vigilance Task
R&D	Research & Development
SOAP	Special Operations Assessment Profile
VAS	Visual Analogue Scale
WASO	Wake After Sleep Onset

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4.	AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used) Paul, M.A.; Gray, G.W.; Nesthus, T.E.; Miller, J.C.

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Background. In support of the Board of Inquiry (BOI) investigating the October 2005 fire on board HMCS Chicoutimi, DRDC Toronto was asked to model crew cognitive effectiveness at the time of the fire and at the time of casualty evacuation approximately 28 hrs after the fire. The results of this modeling effort (based on sleep behaviour estimates) suggested that our submariners were operating at significantly reduced levels of cognitive effectiveness. Therefore DRDC Toronto was tasked to conduct an at-sea trial, this time using real actigraphically-derived sleep data in order to more accurately model the impact of the watch schedule on crew cognitive effectiveness. **Methods.** Twenty-one submariners participated as subjects in this at-sea trial. Three of these subjects were non-watch-standers: Commanding Officer (CO), Coxswain (COXSN) and Chief Engine Room Artificer (CERA), 6 subjects were from the 1-in-2 back-watch, 6 subjects were from the 1-in-2 front-watch, and 6 subjects were from the 1-in-3 engineers' watch. The trial took place on a Canadian submarine during a 13-day transatlantic return to Halifax. All subjects wore wrist activity monitors (actigraphs) in order to measure their daily sleep patterns quantitatively. The subjects also maintained a daily activity and sleep log, and performed daily iterations of the psychomotor vigilance task (PVT). **Results.** The modeled cognitive effectiveness was worse than the previous modeling efforts for Chicoutimi which used sleep behaviour estimates. The activity and sleep log data indicated increasing difficulty arising from sleep and a decrease in subjective levels of 'restedness' over days at sea. Alertness also decreased over days at sea. Each of the 1-in-2 front and back-watches were less 'happy' than their 1-in-3 engineering watch counterparts. While there was no difference in sleepiness between watch system variants or over days at sea, sleepiness levels were consistently elevated to mid-scale levels. Difficulty concentrating, slowed reactions, level of fatigue, work frustration and physical discomfort increased during the trial relative to the pre-trial baseline. **Conclusion.** The current submarine watch schedule is sub-optimal in that it results in worrisome levels of cognitive effectiveness in our submariners. **Recommendation.** An alternative watch schedule which is more sparing of submariner cognitive effectiveness should be developed and implemented, if possible.

Contexte : À la demande de la Commission d'enquête sur l'incendie survenu à bord du NCSM Chicoutimi en octobre 2005, RDDC Toronto a créé un modèle informatisé de l'efficacité cognitive de l'équipage au moment de l'incendie et au moment de l'évacuation des victimes environ 28 heures après l'incendie. Cette modélisation (fondée sur les estimations de conduite du sommeil de l'équipage) a permis de conclure que le niveau d'efficacité cognitive opérationnelle de nos sous-mariniers était considérablement réduit. Par conséquent, RDDC Toronto a été invité à effectuer un essai en mer, en utilisant cette fois des données de sommeil réelles colligées par actigraphie, afin de modéliser plus précisément l'impact des horaires de garde sur l'efficacité cognitive de l'équipage. **Méthodologie :** Vingt et un sous-mariniers ont participé à cet essai en mer. Trois d'entre eux ont été affectés à des postes autres que de garde (Commandant, Capitaine d'armes, et Chef des machines -- CERA); six ont été affectés comme vigies de quart arrière, à raison de un tour de garde sur deux; six ont été affectés comme vigies de quart avant, à raison de un tour de garde sur deux; et six ont été affectés comme mécaniciens chefs de quart, à raison de un tour de service sur trois. L'essai a été réalisé à bord d'un sous-marin canadien, au cours d'un voyage transatlantique de 13 jours, à destination de Halifax. Chacun des participants portait un bracelet moniteur (actigraphe) de ses activités, pour permettre de mesurer quantitativement sa structure de sommeil. Les participants ont aussi

consigné quotidiennement dans un journal leurs heures d'activités et leurs heures de sommeil, et ils ont effectué des itérations quotidiennes de leurs tâches d'attention soutenue (Psychomotor *Vigilance Task* -- PVT). **Résultats :** L'efficacité cognitive de l'équipage, mesurée lors de cet essai en mer, s'est avérée moindre que celle obtenue par modélisation comportementale fondée sur les estimations de conduite du sommeil de l'équipage du Chicoutimi. Les données consignées dans le journal d'activités et de sommeil ont démontré une difficulté croissante des participants à se tirer du sommeil, et une décroissance des niveaux subjectifs de « sensation de repos » à mesure que le nombre de jour en mer augmentait. Le niveau d'acuité intellectuelle des participants est aussi allé en décroissant au fil des jours durant cet essai en mer. Chacune des vigies de quart avant et arrière affectée à un tour de garde sur deux a fait montre d'une attitude moins joyeuse que ses vis-à-vis mécaniciens chefs de quart affectés à un tour de service sur trois. Bien qu'on n'ait constaté aucune différence du niveau de somnolence entre les vigies, ou après un même nombre de jours en mer, les niveaux de somnolence observés se sont tous avérés moyennement élevés. On a aussi constaté chez les participants une difficulté plus grande à se concentrer, des réactions plus lentes, un niveau de fatigue plus élevé, de la frustration au travail, et un inconfort physique accru. **Conclusion :** L'horaire de garde actuel à bord de nos sous-marins est sous-optimal, du fait qu'il entraîne une réduction inquiétante du niveau d'efficacité cognitive de nos sous-mariniers. **Recommandation :** Un nouvel horaire de garde – moins éprouvant pour l'efficacité cognitive du sous-marinier – devrait être élaboré et mis en œuvre, si possible.

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